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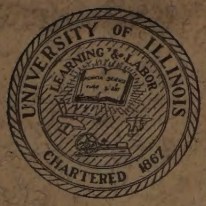
THE HARDENABILITY OF CARBURIZING STEELS

BY

WALTER H. BRUCKNER



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THE HARDENABILITY OF CARBURIZING STEELS

BY

WALTER H. BRUCKNER
RESEARCH ASSISTANT PROFESSOR IN METALLURGICAL ENGINEERING

Steel, Hardenability
Steel - Testing
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THE HARDENABILITY OF CARBURIZING STEELS

I. Introduction

1. *Introductory.*—The problem of the hardenability of carburizing steels has been a special concern of the automotive industry due to the use of carburized and hardened roller bearings and gears. The mass production of such bearings and gears makes it necessary to standardize procedures of carburizing and heat treatment for a consistently uniform product. To obtain such a uniform product the response of the steel to commercially-standardized quenching and heat treatment operations after carburizing must be the same for each bar or gear put through the cycle.

Methods of selecting steels according to their response to a standardized carburizing and hardening cycle have been favorably regarded by the automotive industry, and their laboratories have been engaged in developing such selection methods. As a result of this activity a paper was published by W. E. Jominy and A. L. Boegehold of the General Motors Corporation Research Laboratories staff, entitled "A Hardenability Test for Carburizing Steel."* The paper describes a method of testing according to the following procedure:

(1) A bar 3 inches in length is machined to the dimensions indicated in Fig. 1 and provided with an adapter as shown. It is then placed in a carburizing box and a mixture of one-third old and two-thirds new carburizing compound is packed around the bar. The carburizing box thus prepared is placed in a furnace at 1700 deg. F. for nine hours.

(2) The bar is quickly transferred to a holder on a quenching tank which holds the end of the hot carburized bar in a central position with respect to a jet of water which is allowed to impinge on the cupped end of the bar. The latter is held to a fixed distance of one-half inch from the orifice of the jet. The amount of water issuing from the jet is standardized by means of an orifice diameter of one-half inch and a jet height of 2½ inches when not obstructed by the end of the sample during the quench. The sample is thus quenched at one end from the carburizing temperature of 1700 deg. F. and is allowed to remain on the fixture until the entire bar has come to room temperature. Jominy's tabulated data on the cooling rates along the bar are shown in Table 10.

*Trans. A.S.M. Vol. 26, No. 2, June 1938, pp. 574-599.

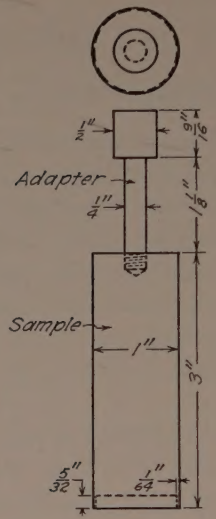

FIG. 1. QUENCH TEST SPECIMEN FOR JOMINY TEST

(3) The bars of steel which have been carburized and quenched are surface-ground along the entire length of one side to a depth of 0.015 inch, and on the diametrically opposite side to a depth of 0.026 inch. A survey of the hardness is made at intervals of one-fourth inch from the water-cooled end to the slowly-cooled end along the center line of each ground surface. The hardenability of various carburized steels is then stated empirically as the distance in inches from the water-cooled end through which the hardness of 600 or more Vickers-Brinell units is attained at the 0.015-inch depth. The limiting hardness value of 600 Vickers-Brinell units is chosen as consistent with the minimum of desired wear resistance for the hardened part in service. Occasionally a higher hardness is obtained at the 0.026-inch depth than at 0.015 inch, but the Jominy hardenability rating is always made for the 0.015-inch depth.

In applying the test described in the foregoing to a series of SAE 4615-4620 steels it was noted by Jominy that steels of apparently like chemical composition and grain size hardened to 600 or more Vickers-Brinell to different distances from the water-cooled end of the carburized bar. Table 5 on page 597 of Jominy's paper shows that out of 12 fine grain SAE 4620 steels, three steels hardened to at least 600 Vickers-Brinell for a distance of 2½ inches from the water-cooled end, three to 1¼ inch, three to ⅞ inch, one to ¾ inch and two to ½ inch.

The reason for such a wide variation of hardenability in apparently similar steels could not be advanced by Jominy and others who discussed the paper at its presentation. It was therefore realized that additional research was required to determine the factors causing low hardenability, and to outline the necessary control procedures in melting and processing the steels to meet hardenability specifications.

2. *Scope of Investigation.*—The aim of the present research was to investigate the hardenability of known low- and high-hardening steels of increasing alloy content in order to determine whether the Jominy method of rating the hardenability of carburizing steels was valid. An intensive study of a series of SAE 4615-4620 steels was then undertaken to determine the factors causing low hardenability.

3. *Acknowledgments.*—This investigation was undertaken as a part of the work of the Engineering Experiment Station, University of Illinois, of which Dean M. L. Enger is the Director, and of the Department of Mining and Metallurgical Engineering of which Professor A. C. Callen was the head.

The helpful counsel of Professor A. C. Callen and of Assistant Professors A. B. Wilder and H. L. Walker of the Department of Mining and Metallurgical Engineering during the progress of the research is gratefully acknowledged.

The aid given to the research by the Timken Roller Bearing Company Research Laboratories of Canton, Ohio, in supplying steels and bar analyses, and in making the many carbon analyses deserves special mention and thanks, as do also the personal attention and interest which were given to the investigation by Dr. Gilbert Soler, manager of research, Dr. Weston A. Hare, formerly research engineer, and Mr. R. K. Lee, research engineer.

Steels were also received from the Republic Steel Corporation through the kindness of Dr. J. L. Burns, Assistant Superintendent of the Wire Division, Grand Crossing Works, Chicago.

II.—Hardenability Tests on Carburized Steels

4. *Preliminary.*—Whenever a new method of testing such as that described by Jominy and Boegehold becomes available it is necessary to determine whether other laboratories can follow the specified procedure and obtain the same data on like materials. The Timken Roller Bearing Company furnished sufficient bar stock of SAE 4620 steels from several of the same bars used by Jominy and Boegehold and

FIG. 2. QUENCH TEST SPECIMEN IN POSITION ON FIXTURE OF QUENCHING TANK WITH WATER JET DIRECTED AT END OF BAR AND DEFLECTED BY CUP END

reported in Table V of the publication cited. A quenching tank was constructed as illustrated in Fig. 2, according to specifications suggested by Jominy and Boegehold. Their procedure in carburizing, quenching, and testing the bars of SAE 4620 steels was followed.

It was found that three bars which had been rated by Jominy's test as having a hardenability of $\frac{3}{4}$, $1\frac{1}{4}$, and $2\frac{1}{2}$ inches, respectively, gave corresponding values of $\frac{5}{8}$, $1\frac{1}{8}$ and 2 inches in the University of Illinois metallurgical laboratory. The order of hardenability is the same as found by Jominy and Boegehold, but the extent of hardening is slightly less. This can be ascribed to the use of a carburizing compound which was available in the laboratory stores instead of the specific carburizer used by Jominy and Boegehold. Hardenability tests made with the type F.S.K. carburizing compound used by them, and which was made available by the Park Chemical Company, indicated that the extent of hardenability could be increased by the use of this material.

The survey of hardenability along the bar when made with the Rockwell diamond cone under a load of 150 kilograms (Rockwell "C," or Rc as it usually appears in the literature) was found to give results inconsistent with the Jominy-Boegehold hardness values, which were obtained with the Vickers-type machine using a 10-kilogram load. A Vickers-type machine was therefore used exclusively for rating the hardenability of carburized steels.

From these preliminary tests the following conclusions could be drawn:

(1) Other laboratories can check the hardenability ratings of the same steels by use of the Jominy method.

(2) To obtain reproducibility of results in various laboratories the procedure of Jominy and Boegehold must be followed, including the use of a similarly-efficient carburizer and a Vickers-type hardness testing machine.

For any particular laboratory the determination of relative hardenability for the steels in use there may be determined with any carburizing compound desired, provided the latter is of uniform efficiency. The experience with carburizers of apparently different efficiencies also suggests the possibility of determining relative carburizing efficiencies by means of a standard steel bar subjected to the Jominy test.

Having established the procedure required to check the results of Jominy and Boegehold it was possible to investigate and make a comparison of hardenability of a series of steels which were expected to have widely differing hardenabilities.

5. *Steels Used.*—The steels whose analyses are given in Table 1 were in bar form; bars 1, 2, 3, 4 were forged from billets, and the rest were hot rolled. All of the bars were annealed at 1650 deg. F. at the mill and furnace-cooled.

6. *Test Procedure.*—Test specimens of all the steels in Table 1 were prepared as illustrated in Fig. 1 and carburized at 1700 deg. F. in a box with solid carburizing compound of the F.S.K. type. One hour was allowed for the sample to come to furnace temperature, and the total time in the furnace was nine hours. The quenching of the sample in the fixture shown in Fig. 2 and the hardness-testing procedure followed the specifications cited in the introduction, and check tests made on the bars indicated that the hardenability ratings could be reproduced to within $\frac{1}{8}$ inch or less. Other tests were made on the surface of the bars with the Rockwell machine using the diamond cone and a

TABLE 1

ANALYSES OF VARIOUS SAE TYPE STEELS WITH INCREASING ALLOY CONTENT

Bar	SAE Type	Content, per cent									Total Alloy Content Mn, Si, Cr, Ni, Mo, V per cent	McQuaid-Ehn Grain Size
		C	Mn	Si	Cr	Ni	Mo	V	P	S		
1	1020	0.20	0.48	0.22	0.12	0.19	0.02	....	0.016	0.022	1.03	7-8
2	5115	0.20	0.56	0.28	0.83	0.17	0.02	....	0.027	0.027	1.86	6-8
3	4115	0.20	0.38	0.24	0.91	0.18	0.20	....	0.011	0.011	1.91	4-7
4	6115	0.17	0.48	0.25	1.02	0.14	0.02	0.18	0.011	0.015	2.09	6-8
5	3115	0.16	0.51	0.24	0.63	1.21	0.02	....	0.016	0.022	2.61	5-7
6	4315	0.17	0.67	0.25	0.50	1.73	0.25	....	0.015	0.020	3.40	6-8
7	2315	0.17	0.54	0.27	0.09	3.48	0.02	....	0.017	0.021	4.40	7-8
8	4815	0.18	0.52	0.27	0.10	3.53	0.24	....	0.011	0.012	4.66	7-8
9	2315	0.10	0.49	0.28	1.57	3.50	0.01	....	0.011	0.018	5.85	5-7

TABLE 2

HARDENABILITY OF VARIOUS SAE STEELS; CARBURIZED, QUENCHED, AND HARDNESS TESTED ACCORDING TO JOMINY AND BOEGEHOLD

Bar	SAE Type	Total Alloy Mn, Si, Cr, Ni, Mo, V per cent	Distance from Water-cooled End for 600 or Higher Vickers-Brinell Hardness		Distance from Water-cooled End for a Rockwell C Hardness of 54 or Higher on the Surface of the Bar in.
			at 0.015-inch depth in.	at 0.026-inch depth in.	
1	1020	1.03	1/16+	1/8+	less than 1/4
2	5115	1.86	1/2+	1/2+	1/2+
3	4115	1.91	1+	1+	1
4	6115	2.09	1/2+	1/2+	1/2+
5	3115	2.61	3/4	1/2+	3/4+
6	4315	3.40	2 1/2	2 1/2	2 1/2
7	2315	4.40	1/2+	3/4+	1/2+
8	4815	4.66	2 1/2	2 1/2	2 1/2
9	2315	5.85	3/4+	2 1/2	2 1/2

load of 150 kilograms (Rockwell "C" or Rc values). These Rockwell tests were made on the surface of the bars before they were ground to depths of 0.015 and 0.026 inch for Vickers hardness tests.

7. *Discussion of Data.*—The results of hardenability tests on the steels of Table 1 are given in Table 2. The rating of the hardenability of the steels in the carburized condition is given for the 0.015- and 0.026-inch depths for the Vickers-Brinell hardness test, and for the Rockwell C hardness on the surface. For the latter, a reading of 54 Rockwell "C" is equivalent to 600 Vickers-Brinell. The readings were usually taken every 1/4 inch along the bar starting from the water-cooled end. Therefore, the distances are reported on a plus or minus basis, the sign indicating a hardenability between the distance given and the next 1/4 inch. The distance to which the carburized bar hardens does not depend directly on total alloy content, since bars 4, 5, and 7 did not harden to the distance consistent with their higher alloy content. A comparison of bars 1 and 2 indicates the effectiveness of a small addition of chromium, and bar 3 the increased effect of the chromium when a higher molybdenum content is present. The larger grain size of bar 3 may also have been effective in increasing the hardenability.

For bars 2 and 4, with practically the same analysis except for a higher chromium content in bar 4, we find the latter is of the same order of hardenability as bar 2, notwithstanding the additional chromium content.

Bars 7 and 9 are of practically the same analysis except for a

higher chromium content in bar 9, which may have been effective in increasing its hardenability. On the other hand bars 7 and 8 are also practically identical in analysis except for an increase of 0.22 per cent molybdenum in bar 8. If the small increase in molybdenum were alone responsible for the increased hardenability of bar 8 it would appear to be out of proportion to the small change in analysis.

In the region where the hardness test was made the carbon content has been increased to a considerable degree during the carburizing operation and it was of interest to determine how the steels of bars 1 to 9 would harden in the uncarburized condition.

III. Hardenability Tests on Uncarburized Steels

8. *Preliminary.*—A method of rating the hardenability of uncarburized steels was published under the title "Quantitative Hardenability" by J. L. Burns, T. L. Moore, and R. S. Archer of the Republic Steel Company.* The method consists of the following procedure, and hereafter will be referred to in this bulletin as the "Burns test":

(1) A bar of steel is machined to one inch in diameter and 4 inches in length. The surface of the bar is finished on a lathe with No. 3 emery cloth.

(2) The bar thus prepared is heated for 40 minutes to temperatures recommended for the particular grade of steel in the A.S.M. Handbook. These temperatures are usually 40 to 50 deg. F. above the A_{c3} critical point on slow heating. The bar is then quenched (fully immersed and agitated) in water at room temperature, and cross-sectioned in the middle to obtain a disk for hardness testing.

(3) Hardness tests are made on the cross-sectioned disk after a final polish of the surface with 240-grain alundum on a wet wheel. The hardness tests are made with the Rockwell C penetrator using a load of 150 kg., the indents being made at $\frac{1}{16}$-inch intervals from the center along four 45-deg. diameters. At $\frac{1}{16}$ inch from the center, hardness tests are made on only two diameters 90 deg. apart, since the tests would otherwise be so crowded as to be unreliable. Additional tests are made on the outer cylindrical surface $\frac{1}{8}$ inch from the prepared face, and opposite the four diameters on the cross-sectioned face.

This hardness test provides data which are expressed as an S.A.C. rating, i.e., surface, average, and center hardness. The hardenability of the particular bar may also be expressed on a percentage basis by dividing the surface hardness into the average and multiplying by 100.

*Trans. A.S.M. Vol. 26, No. 1, Jan.-Mar., 1938, pp. 1-22.

TABLE 3
COMPARISON OF HARDENABILITY OF CARBURIZED AND UNCARBURIZED STEELS OF VARIOUS SAE TYPES

Bar	SAE Type	Total Alloy Content per cent	Rating of Hardenability Carburized and Tested According to Jominy		Hardenability Uncarburized According to Burns per cent	*SAC* Rating		
			at 0.015-in. Depth in.	at 0.026-in. Depth in.		*S* (surface)	*A* (average)	*C* (center)
1	1020	1.03	1/16+	1/8+	48.2	45	21.7	14.5
2	5115	1.86	1/2+	1/2+	78.2	44	34.8	29
3	4115	1.91	1+	1+	77.0	47	36.2	30
4	6115	2.09	1/2+	1/2+	77.2	42	32.4	28
5	3115	2.61	3/4	1/2+	74.8	42	31.4	25
6	4315	3.40	2 1/2	2 1/2	88.5	46	40.7	37
7	2315	4.40	1/2+	3/4+	78.2	46	35.9	29
8	4815	4.66	2 1/2	2 1/2	89.9	46	41.4	39
9	2315	5.85	3/4+	2 1/2	95.8	40.5	38.8	37

The percentage hardenability value therefore represents the extent to which the bar has attained its maximum *possible* hardenability under the conditions of test.

The "Burns test" was employed as described for a determination of the hardenability of the steels shown in Table 1.

9. *Discussion of Data.*—The results of the tests are given in Table 3, where they are compared with the hardenability as determined on a "Jominy bar" end-quenched in the carburized condition. The results of the "Burns test" on uncarburized bars are given in Fig. 3 as a graph of Rockwell C hardness versus distance from the center of the bar.

The agreement of the hardenability in the carburized condition with the percentage hardenability in the uncarburized condition is excellent when considered as three ranges of low, intermediate, and high hardenability. Thus bar 1 with a hardenability of less than 1/4 inch has a per cent hardenability below 50, the intermediate range of 1/2- to 1-inch hardenability for bars 2, 3, 4, 5, and 7 corresponding to a percentage range of 77 to 78.2, and the high-hardening range of 2 1/2 inches for bars 6, 8, and 9 corresponding to a percentage hardenability above 80. The agreement in the intermediate range is not exact, thus indicating that the absorption of carbon during carburizing, and the lower cooling rate as the distance from the water-cooled end of the Jominy bar increases, have changed the original hardening characteristics as determined by the Burns test in the uncarburized condition.

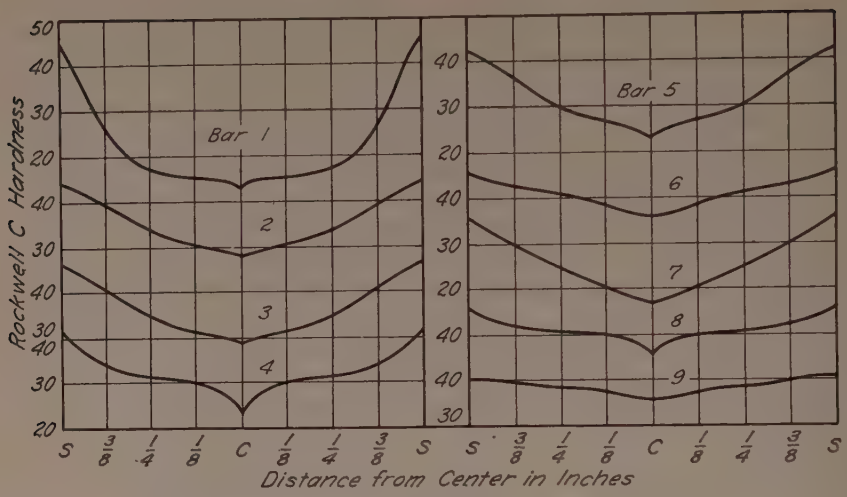

Fig. 3. Hardness Contours in 1-inch Round Uncarburized Bars

It should be noted that Burns and his associates consider the surface hardness, S, to be directly related to the carbon content, provided that the carbon is all in solution in the austenite before quenching, and provided that the critical cooling rate is exceeded without producing retained austenite. This relationship of surface hardness, S, to carbon content has been realized in general for the steels shown in Table 3, except for bars 4 and 5, where the S value is lower than was expected from the carbon contents reported.

The foregoing comparisons of hardenability by the Jominy and the Burns methods were obtained for two different conditions, carburized and uncarburized bars, respectively. A hardenability test of the uncarburized steels by means of the Jominy method produced a hardness of 600 Vickers-Brinell only at distances so close to the water-cooled end as to require hardenability ratings for the various steels to be based on rather delicate measurements of distances of less than ¼ inch. Hardenability ratings of uncarburized steels of low hardenability can therefore be more easily made by means of the Burns test.

IV. Hardenability of SAE 4615-4620 Steels for Carburizing

10. *Materials.*—The Timken Roller Bearing Company and the Republic Steel Company furnished a series of bars of SAE 4615-4620 steels whose analyses are given in Table 4. All of the bars were either

annealed in the mill or in the laboratory for one hour at 1650 deg. F.. and furnace cooled. All except three bars, 30, 39, and 40 are fine grained. In the series of steels shown in Table 4 bars 10 to 15 were selected in the mill as representing heats which were melted and processed in the same manner, and are as nearly identical in chemical analysis, grain size, and total alloy as possible. In this bulletin these steels are called "like heats," and they are a special group which were intensively studied. Bar 16 has been included with these like heats since it is similar in composition except for a slightly higher chromium content. It was, however, not included with bars 10 to 15 in the special tests.

The remainder of the steel bars were grouped according to contents of manganese and chromium, since the greatest variation in the analysis occurs in these elements.

For a few of the bars the only information available as to furnace practice was that they were melted in the open hearth.

The specifications on a percentage basis for the SAE 4615 and 4620 grades of steel are as follows:

	C	Mn	Ni	Mo	Si	P	S
SAE 4615...	0.10-0.20	0.40-0.70	1.65-2.0	0.20-0.30	0.15-0.30	0.04 max.	0.05 max.
SAE 4620...	0.15-0.25	0.40-0.70	1.65-2.0	0.20-0.30	0.15-0.30	0.04 max.	0.05 max.

All of the steels shown in Table 4 are within the specification which, however, does not include any chromium content.

11. *Discussion of Data.*—All of the steels in Table 4 were subjected to the Jominy bar (carburized) and Burns (uncarburized) test procedures which are described in detail in Chapters I and III.

The hardenabilities of the various bars are given in Table 5. Figure 4 shows the variation in hardness with distance from the water-cooled end for the Jominy bar test, while Fig. 5 shows the hardness contours obtained in the Burns test.

The "like heats" of steel of bars 10 to 16 are not alike in their response to carburizing and quenching, as shown in the results from the Jominy-bar hardenability test. They also are not alike in response to heat treatment in the uncarburized condition, as indicated in the results from the Burns hardenability test. The full 2½-inch hardenability is obtained for bars 11 and 16 only, and occurs at different depths, 0.015 inch and 0.026 inch, respectively. The percentage hardenability for the two bars in the Burns test is above 80, which is a greater hardenability than is obtained for the other steels in this group. However, bar 12 has a Burns test hardenability of 79.4 per cent which

TABLE 4

ANALYSES OF VARIOUS SAE 4615-4620 STEELS FOR CARBURIZING

Bar	Content, per cent								Total Alloy Mn, Si, Cr, Ni, Mo per cent	McQuaid-Ehn Grain Size	Furnace Practice*
	C	Mn	Si	Cr	Ni	Mo	P	S			
Group 1. "Like" Heats											
10	0.19	0.55	0.29	0.14	1.74	0.24	0.013	0.017	2.96	8	30 TEAF
11	0.19	0.55	0.29	0.17	1.74	0.24	0.018	0.015	2.99	8	30 TEAF
12	0.16	0.55	0.30	0.17	1.74	0.24	0.013	0.019	3.00	7-8	30 TEAF
13	0.20	0.58	0.30	0.12	1.75	0.25	0.017	0.016	3.00	7-8	100 TOH
14	0.19	0.55	0.30	0.18	1.74	0.24	0.014	0.016	3.01	8	30 TEAF
15	0.18	0.55	0.28	0.15	1.75	0.23	0.014	0.020	2.96	8	30 TEAF
16	0.19	0.55	0.30	0.20	1.75	0.25	0.018	0.016	3.05	8	100 TEAF
Group 2. Heats with Low Cr. (less than 0.14) and Mn 0.52-0.60											
17	0.20	0.55	0.30	0.10	1.75	0.23	0.015	0.020	2.95	6-8	100 TOH
18	0.17	0.58	0.26	0.08	1.74	0.28	0.018	0.020	2.94	7-8	OH
19	0.15	0.55	0.22	0.04	1.82	0.25	0.117	0.027	2.88	7-8	OH
20	0.18	0.53	0.27	0.10	1.75	0.24	0.015	0.019	2.89	5-8	100 TOH
21	0.20	0.55	0.26	0.11	1.73	0.23	0.020	0.015	2.88	5-8	30 TEAF
22	0.15	0.52	0.28	0.11	1.73	0.23	0.019	0.022	2.87	5-8	30 TEAF
23	0.19	0.55	0.25	0.09	1.74	0.23	0.018	0.017	2.86	5-8	100 TOH
24	0.17	0.55	0.20	0.03	1.84	0.24	0.016	0.024	2.86	7-8	OH
25	0.21	0.60	0.22	0.04	1.72	0.25	0.016	0.022	2.83	7-8	OH
Group 3. Heats with High Cr. (more than 0.20) and Mn 0.54-0.55											
26	0.22	0.55	0.30	0.28	1.75	0.22	0.016	0.013	3.10	8	30 TEAF
27	0.16	0.54	0.29	0.22	1.72	0.23	0.022	0.018	3.00	5-8	100 TOH
28	0.22	0.55	0.30	0.28	1.75	0.22	0.016	0.013	3.10	6-8	30 TEAF

TABLE 4.—(CONCLUDED)
ANALYSES OF VARIOUS SAE 4615-4620 STEELS FOR CARBURIZING

Bar	Content, per cent								Total Alloy Mn, Si, Cr, Ni, Mo per cent	McQuaid-Ehn Grain Size	Furnace Practice*
	C	Mn	Si	Cr	Ni	Mo	P	S			
Group 4. Heats with Low Cr. (less than 0.14) and Low Mn (0.42-0.51)											
29	0.16	0.42	0.19	0.10	1.75	0.25	0.022	0.018	2.71	8	30 TEAF
30	0.16	0.48	0.22	0.10	1.77	0.24	0.018	0.022	2.81	2-3	100 TOH
31	0.16	0.50	0.23	0.13	1.75	0.23	0.015	0.016	2.84	7-8	100 TOH
32	0.16	0.48	0.29	0.12	1.76	0.26	0.017	0.019	2.91	5-8	100 TOH
33	0.16	0.51	0.25	0.12	1.75	0.23	0.019	0.019	2.86	5-8	100 TOH
34	0.19	0.48	0.25	0.10	1.77	0.24	0.016	0.017	2.84	5-8	100 TOH
35	0.21	0.49	0.26	0.11	1.74	0.24	0.015	0.017	2.84	7-8	100 TOH
36	0.16	0.50	0.27	0.08	1.72	0.23	0.016	0.019	2.80	5-8	30 TEAF
37	0.14	0.43	0.21	0.08	1.76	0.22	0.015	0.016	2.70	5-8	30 TEAF
38	0.17	0.49	0.21	0.02	1.77	0.21	0.018	0.022	2.70	7-8	OH
Group 5. Heats with High Cr. (more than 0.20) and Low Mn 0.36-0.45											
39	0.20	0.36	0.14	0.25	1.75	0.24	0.013	0.014	2.74	3-4, 7-8	30 TEAF
40	0.17	0.45	0.25	0.20	1.74	0.21	0.014	0.013	2.85	3-4	100 TEAF
Group 6. Heats with Medium Cr. (0.14-0.19) and Mn 0.52-0.62											
41	0.15	0.52	0.28	0.14	1.72	0.24	0.014	0.015	2.95	5-8	100 TOH
42	0.19	0.57	0.25	0.14	1.76	0.24	0.015	0.018	2.96	6-8	100 TOH
43	0.19	0.62	0.23	0.14	1.71	0.24	0.016	0.018	2.94	7-8	100 TOH
44	0.18	0.60	0.28	0.19	1.74	0.24	0.015	0.022	3.05	7-8	100 TOH

*For furnace practice the abbreviations are: T for ton, E.A.F. for electric arc furnace, and O.H. for open hearth.

TABLE 5

HARDENABILITY OF SAE 4615-4620 STEELS IN CARBURIZED AND UNCARBURIZED CONDITION

Bar	McQuaid-Ehn Grain Size	Total Alloy per cent	Jominy Bar Hardenability = Distance in Inches to Which Carburized Bar Hardens to at least 600 Vickers-Brinell		Burns Test of Uncarburized Bars (all quenched from 1525 deg. F.)			
					Per cent Hardenability $\frac{A}{S} \times 100$	*SAC* Rating		
			at 0.015-in. Depth	at 0.026-in. Depth		*S* (Surface)	*A* (Average)	*C* (Center)
Group 1. "Like" Heats								
10	8	2.96	1½+	¾	73.3	45.5	33.3	28.5
11	8	2.99	2½	1	80.7	45.5	36.7	31.5
12	7-8	3.00	1 +	¾+	79.4	43.6	34.6	30.0
13	7-8	3.00	¾+	½+	77.3	46.0	33.5	30.0
14	8	3.01	1 +	½+	75.0	47.0	35.2	29.0
15	8	2.96	¾+	¾	73.7	44.0	32.4	28.0
16	8	3.05	1	2½	80.3	44.5	35.7	30.0
Group 2. Low Cr. (less than 0.14) with Mn 0.52-0.60								
17	6-8	2.95	¾+	½+	78.8	46.0	36.3	30.0
18	7-8	2.94	1½+	½+	77.8	44.0	34.3	30.0
19	7-8	2.88	½+	¼+	73.2	41.0	30.0	23.0
20	5-8	2.89	¼+	⅛+	75.0	46.0	34.5	28.0
21	5-8	2.88	¼	¼+	77.0	46.0	35.4	31.0
22	5-8	2.87	¼+	⅛+	76.8	44.0	33.8	28.0
23	5-8	2.86	½+	⅛+	77.5	47.0	36.4	32.0
24	7-8	2.86	½+	¼+	75.2	45.0	33.8	28.5
25	7-8	2.83	¾+	1¼	77.3	47.5	36.7	31.0
Group 3. High Cr. (more than 0.20) with Mn 0.54-0.55								
26	8	3.10	2½	2½	76.5	49.0	37.5	32.0
27	5-8	3.00	2½	½+	77.8	45.0	35.0	30.5
28	6-8	3.10	¾+	⅛	80.6	50.5	40.7	28.0

TABLE 5.—(CONCLUDED)
HARDENABILITY OF SAE 4615-4620 STEELS IN CARBURIZED AND UNCARBURIZED CONDITION

Bar	McQuaid-Ehn Grain Size	Total Alloy	Jominy Bar Hardenability = Distance in Inches to Which Carburized Bar Hardens to at least 600 Vickers-Brinell		Burns Test of Uncarburized Bars (all quenched from 1525 deg. F.)			
					Per cent Hardenability $\frac{A}{S} \times 100$	*SAC* Rating		
			at 0.015-in. Depth	at 0.026-in. Depth		*S* (surface)	*A* (average)	*C* (center)
Group 4. Low Cr. (less than 0.14) and Low Mn (0.42-0.51)								
29	8	2.71	1/4	1/4 +	78.3	43.0	33.7	27.0
30	2-3	2.81	2 1/2	3/4 +	70.5	46.0	32.4	24.0
31	7-8	2.84	1/2 +	1/2 +	70.8	44.5	31.5	22.0
32	5-8	2.91	3/8 +	−1/8	85.8	46.0	39.5	35.0
33	5-8	2.86	3/4	1/4 +	81.5	46.0	37.5	33.0
34	5-8	2.84	1/2 +	1/4 +	77.7	48.0	37.3	29.0
35	7-8	2.84	1/2 +	1/4 +	80.8	48.0	38.8	32.0
36	5-8	2.80	1/2 +	1/4 +	76.3	45.0	35.9	31.5
37	5-8	2.70	1/2	1/4	68.3	42.6	29.1	23.0
38	7-8	2.70	1/4 +	1/4 +	76.8	45.0	34.6	28.0
Group 5. High Cr. (more than 0.20) and Low Mn 0.36-0.45								
39	(3-4) (7-8)	2.74	1 +	1 3/4	79.8	46.0	36.7	32.0
40	3-4	2.85	2 1/2	2 1/2	78.3	46.0	36.0	30.0
Group 6. Medium Cr. (0.14-0.19) and Mn 0.52-0.62								
41	5-8	2.95	1/4 +	− 1/8	74.0	45.0	33.3	28.0
42	6-7	2.96	1/4 +	1/4 +	76.4	47.0	35.9	31.0
43	7-8	2.94	3/4 +	3/4	81.1	47.0	38.1	33.0
44	7-8	3.05	3/4 +	3/4 +	79.5	44.0	35.0	29.0

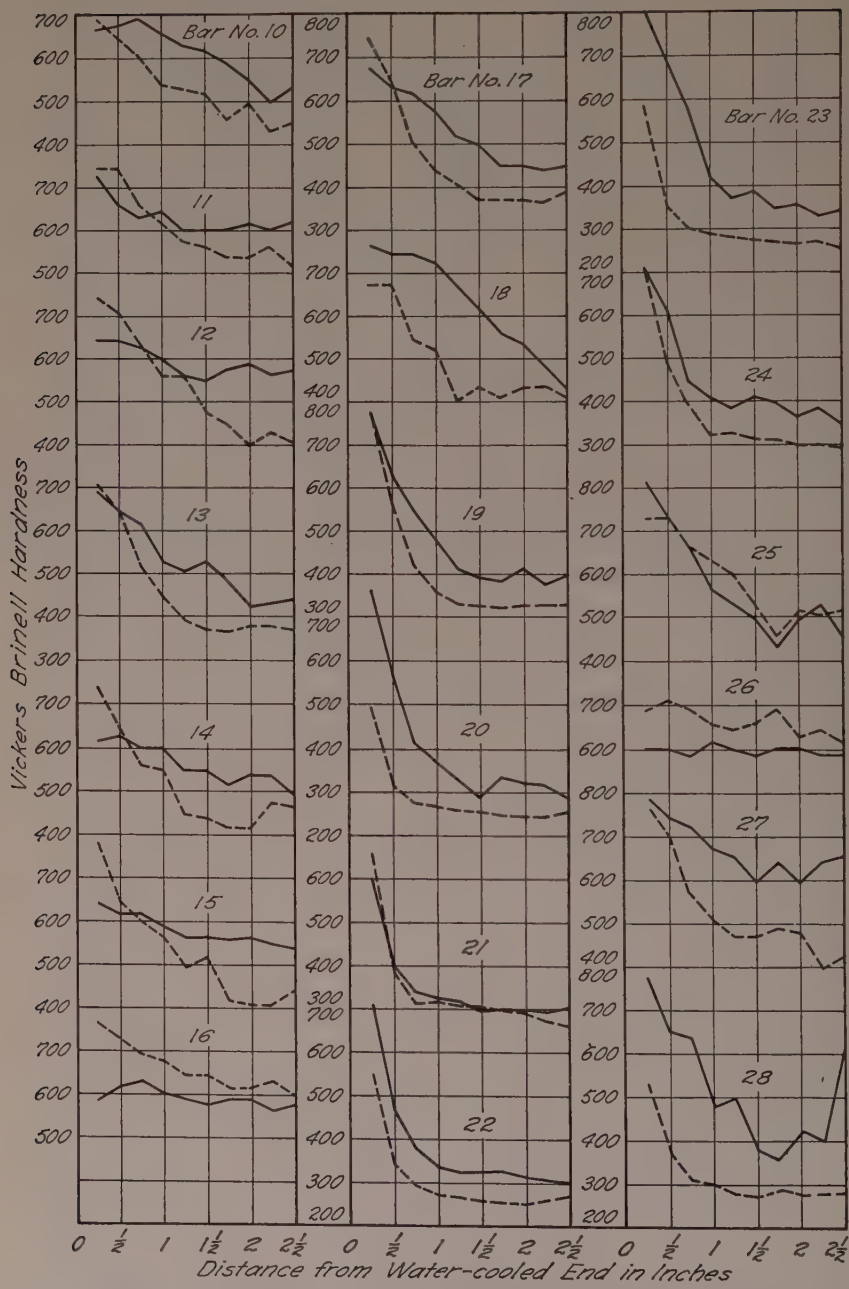

FIG. 4. HARDNESS SURVEY OF CARBURIZED SAE 4615-4620 STEELS

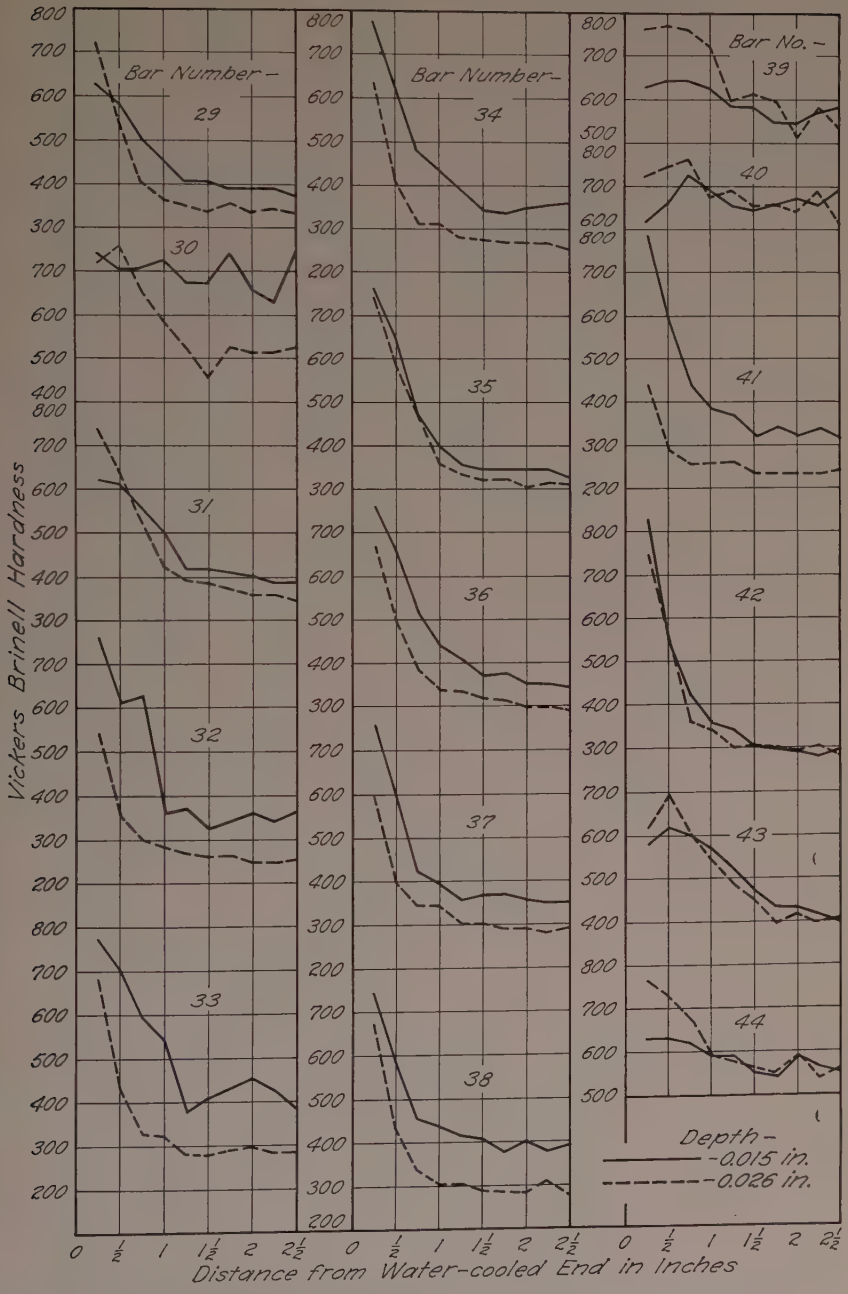

FIG. 4 (CONCLUDED). HARDNESS SURVEY OF CARBURIZED SAE 4615-4620 STEELS

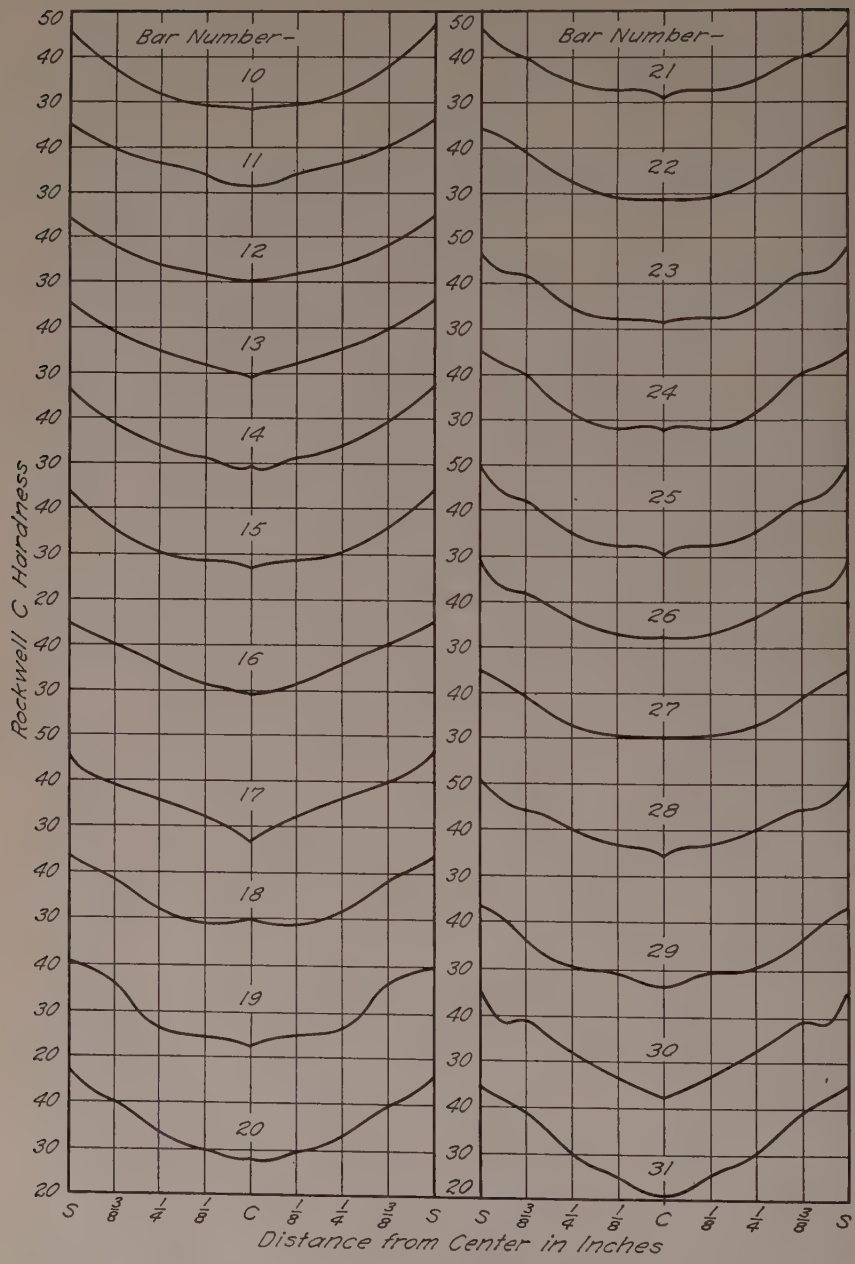

FIG. 5. HARDNESS CONTOURS IN 1-INCH ROUND UNCARBURIZED SAE 4615-4620 BARS

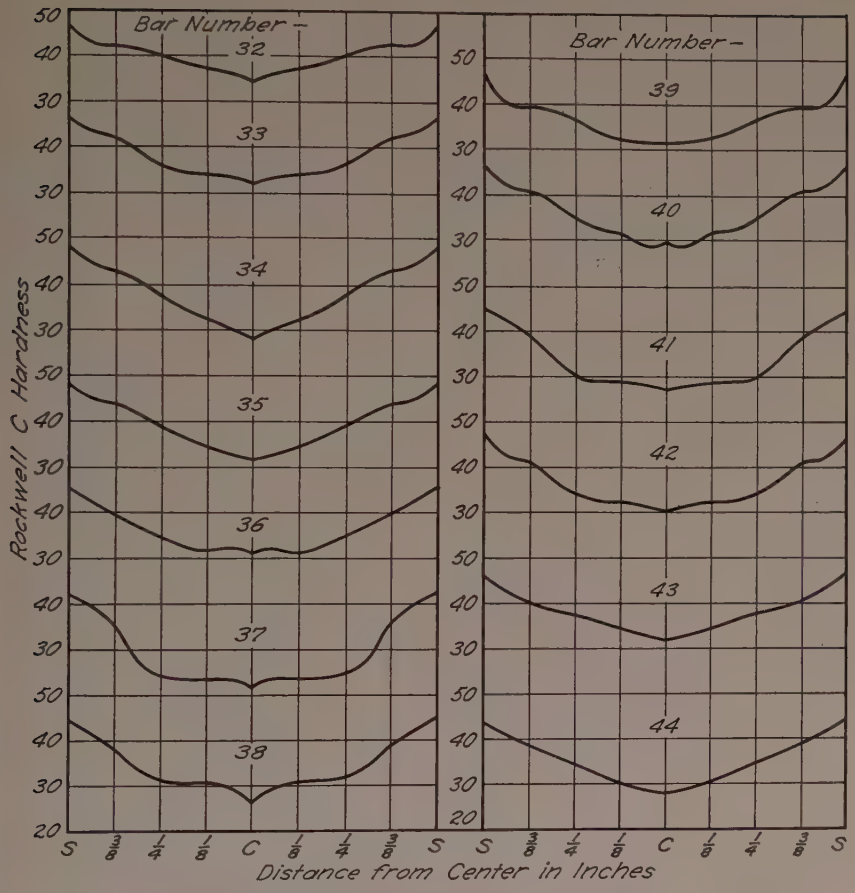

FIG. 5 (CONCLUDED). HARDNESS CONTOURS IN 1-INCH ROUND UNCARBURIZED SAE 4615-4620 BARS

is close enough to 80 per cent to warrant the expectation of a correspondence in the Jominy bar hardenability for bar 12 and for bars 11 and 16, if the two hardenabilities were related. However, this is not the case, and bar 12 hardens to only one inch plus at the 0.015-inch depth, while bar 10, with a hardenability of only 73.3 per cent, hardens to 1½ inches at the 0.015-inch depth. It must, therefore, be concluded that a prediction of hardenability of the carburized Jominy bar cannot be made by means of a Burns test on the uncarburized material of the SAE 4615-type steels.

Further tests were made on bars 10 to 15 of the like heats and the results are discussed in detail in Chapter V of this bulletin.

The steels in group 2 of Table 5 are the low chromium steels with manganese ranging from 0.52 to 0.60 per cent. The variation in hardenability for the Jominy test (¼ to 1½ inches) and the Burns test (75 to 78.8 per cent) is less than the variation for the "like heats" of steel in group 1 of Table 5. In general, the steels harden to a maximum of between ¾ inch and one inch. However, several steels (20, 21, and 22) harden to a distance only slightly greater than the plain carbon steel, bar 1 of Table 2, which has an alloy content of only one per cent. The bar, 18, of highest hardenability in this group has a hardenability of 1½ inches, yet its chromium content is lower than that of others of lower hardenability, and its manganese and molybdenum contents are slightly above the average for the group. It appears, therefore, that in this group with low chromium content the desired hardenability of 2½ inches cannot be obtained.

The third group of steels (26, 27, and 28) with high chromium and normal manganese of 0.54-0.55 per cent is interesting, since two bars, 26 and 27, harden to the full 2½ inches at the 0.015-inch depth, while bar 28, which is identical with 26 as to chemistry, furnace practice, and total alloy, exhibits shallow hardening. The grain-size of bar 28 being somewhat coarser than that of bar 26 would be expected to correspond to an increase in hardenability rather than a decrease as indicated. The Burns-test hardenability follows this grain-size difference, since bars 27 and 28 have higher percentage hardenabilities than bar 26. The effect of chromium is again indefinite, since a high content of this element in one bar does not assure high hardenability in another bar.

The fourth group of steels (29 to 38) is low in chromium, manganese, and total alloy. These steels are shallow hardening when fine grained. The only one of the group, bar 30, which has a coarse grain hardens to 2½ inches, thus fulfilling expectations from all previous experience with respect to the effect of grain size in the hardening of steels. However, the Burns test on bar 30 gives a low hardenability rating. Further inconsistencies between the Jominy and the Burns tests for hardenability are shown for bar 32 which has the highest rating of any of the steels treated by the Burns test and yet has a low Jominy rating. Bars 33 and 35 are also examples of this inconsistency.

The steels of group five, 39 and 40, are coarse-grained with high chromium, low manganese, and low total alloy. Fair hardenability is exhibited by bar 39, and high hardenability by bar 40, due to the

coarse grain being more effective in increasing hardenability than the unfavorable analysis is in decreasing it. The presence of mixed coarse- and fine-grain sizes in bar 39 may be responsible for its failure to attain the 2½ inches of hardening experienced with both uniformly-coarse-grain steels, bars 30 and 40, but further tests with such steels would be necessary to make a definite statement of fact.

The last group of steels in Table 5 (41 to 44) all have high alloy content and low hardenability. The first two bars, 41 and 42, have a lower hardenability than some of the bars in the preceding group with much lower total-alloy content. The causes of these inconsistent relationships have not been determined, and therefore additional research is suggested for future consideration.

12. *Summary and Conclusions from the Data in Table 5.*—The control of the chemical composition of the SAE 4615-4620 steels within the specification limits does not assure a high hardenability in the Jominy bar test. The control of total-alloy content to a value above 2.90 per cent, with a chromium content of more than 0.17 per cent, increases the frequency with which higher hardenability is obtained, but does not assure higher hardenability. Variable factors other than grain size and chemical composition appear to have a predominant effect since the like heats of steel with the same grain size and chemical composition behave differently in hardening. The variable factors and their effect on hardenability are discussed in the next section.

On the basis of a specification for fine-grain SAE 4615-4620 steel which will harden to 2½-inches at the 0.015-inch depth when carburized and subjected to the Jominy bar test, we have, in Table 5, 32 steels of fine-grain type out of which only three, bars 11, 26, and 27, are acceptable. Another, bar 16, hardens to 2½ inches, but at the 0.026-inch depth and not at the 0.015-inch depth.

The occurrence of a higher hardenability rating at the 0.026-inch depth than at the 0.015-inch depth is not usual in this type of steel, since in the entire series of bars in Table 5 only bars 16 and 25 of fine-grain type and bar 39 of mixed coarse- and fine-grain type exhibit this tendency to a marked extent. However, the Jominy test does not indicate at what depth maximum hardenability is attained for any bar tested at the arbitrary depths of 0.015 and 0.026 inch, since it is entirely possible for maximum hardenability to occur at any depth between the surface and 0.015 inch depth or between the 0.015 and 0.026 inch depths. This is actually the case, as will be shown later.

The suggested use of the Jominy bar test for hardenability of carburizing steels is based on the following assumption: If a steel bar were hardened to, say, 2½ inches, and any object, such as a large gear or bearing, were taken, carburized at 1700 deg. F., and quenched in such a manner that the surface-cooling rate was the same as the surface-cooling rate for the Jominy bar at 2½ inches from the water-cooled end, then the hardness value obtained at various depths in the Jominy bar should be the same at the same depths as for the gear or bearing. Assuming this premise to hold in all cases for the steels in Table 5, it can be seen that the shipment of a lot of 32 such steel bars to the automotive industry would entail considerable testing on its part to define hardenabilities, or, if they were put into production without testing, would result in a wide variation of properties for the finished parts if all were carburized and heat-treated in the same manner. More data are needed to determine the quantitative relationship between the Jominy test for hardness of carburized steels and the hardness established by the varying carburizing conditions and quenching rates in commercial parts such as gears or bearings of large and small dimensions. In order to obtain such data it would be necessary to determine whether the distribution of carbon during the carburizing of any section larger or smaller is the same as that established in the one-inch diameter Jominy bar. It is inconceivable that the carbon gradients (carbon content versus distance from the surface to core of carburized bar, see Fig. 9) would be the same except for approximately the one-inch-diameter bar; therefore, the direct application of the Jominy test would appear to be invalid for any section departing to an appreciable extent from the one-inch-diameter cross-section.

V. Special Tests on the Like Heats of SAE 4615-4620 Carburizing Steels—

Group 1 of Tables 4 and 5

13. *Introductory.*—The lack of uniformity in the Jominy-bar hardenability of the like heats of steel raised several questions as to the uniformity of the absorption of carbon for the bars, the hardenability for the bars at other than the 0.015- and 0.026-inch depths specified, and the relationship of the Jominy-bar hardenability to that actually obtained in a carburized and quenched bar.

It was also considered important to determine the effect of carbon content on the hardenability of the steels of this type when there was no carbon gradient present in the bar such as exists when a bar con-

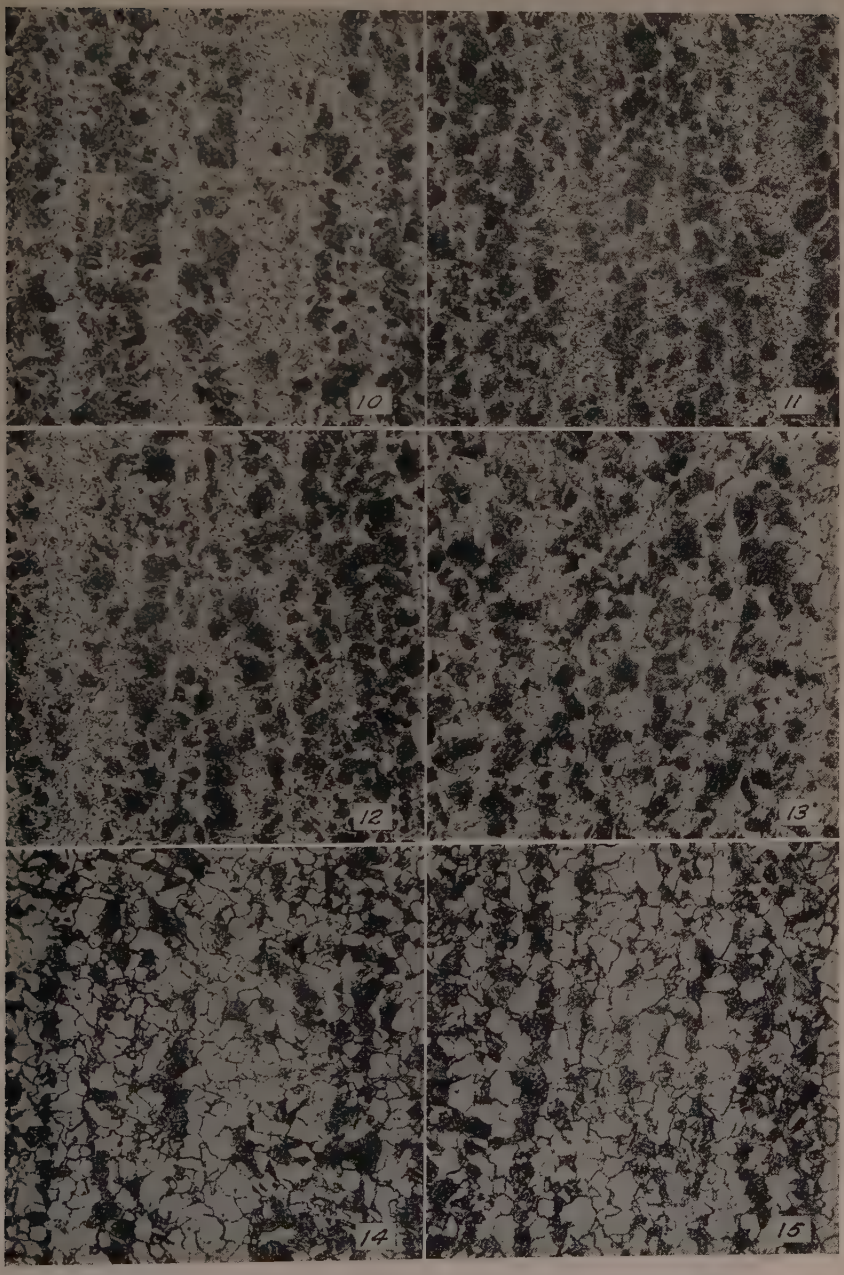

FIG. 6. MICROSTRUCTURES OF "AS RECEIVED" SAE 4615-4620 STEELS; BARS 10 TO 15 AT MAGNIFICATION OF 200X

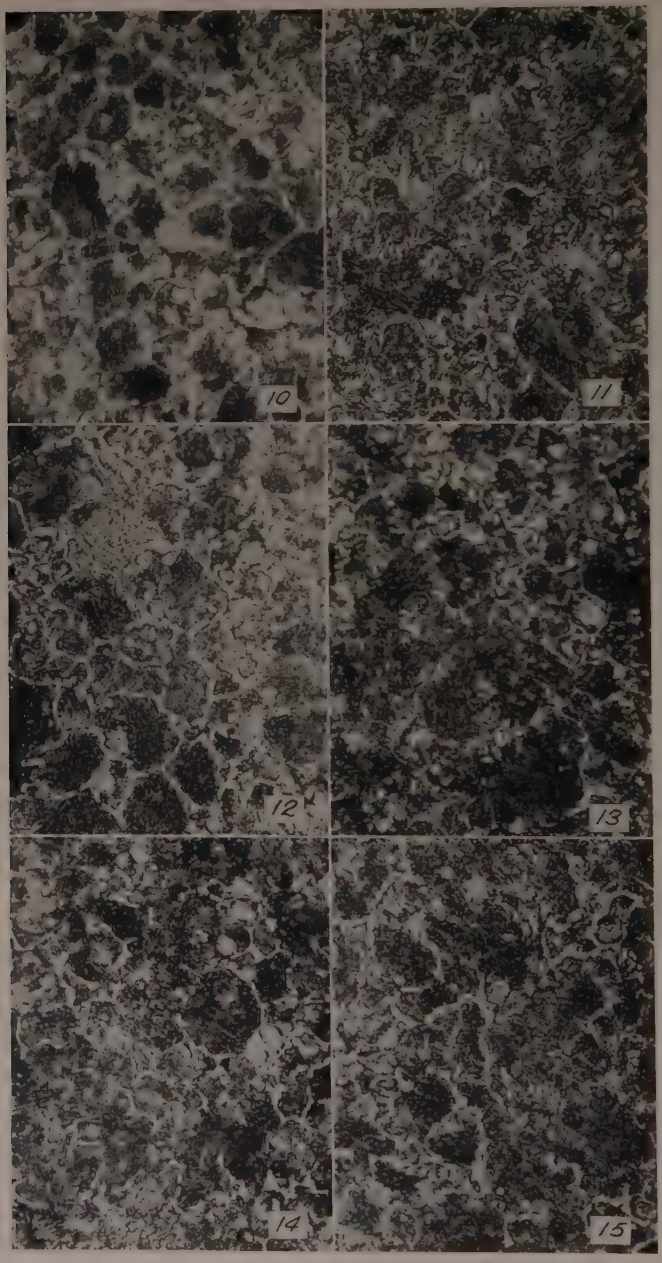

FIG. 7. MICROSTRUCTURES IN HYPEREUTECTOID ZONE OF MCQUAID-EHN, GRAIN SIZE SAMPLES; BARS 10 TO 15 AT MAGNIFICATION OF 500X

TABLE 6

CARBON ANALYSES FOR CARBON GRADIENT TESTS; CARBON PERCENTAGE AT VARIOUS DEPTHS

Cut No. Depth, in.	1 0.0-0.005	2 0.005-0.010	3 0.010-0.015	4 0.015-0.020	5 0.020-0.025	6 0.025-0.030	7 0.030-0.035	8 0.035-0.040
Bar No.	Like Heats							
10	1.00	0.97	0.90	0.82	0.74	0.67	0.59	0.53
11	1.00	0.96	0.89	0.82	0.75	0.67	0.60	0.53
13	1.00	1.00	0.92	0.85	0.79	0.72	0.63	0.56
14	0.99	0.97	0.92	0.86	0.77	0.68	0.61	0.53
15	1.05	1.00	0.92	0.84	0.78	0.71	0.63	0.56
	Low Hardenability Heat							
29	1.03	1.01	0.94	0.87	0.78	0.70	0.64	0.56
Average	1.010	0.985	0.915	0.845	0.768	0.692	0.617	0.545
Carbon Percentage at Various Depths, from Average Curve of Fig. 26								
Depth, in.	0.000	0.005	0.010	0.015	0.020	0.025	0.030	0.035
Average of all bars	1.02	1.01	0.95	0.88	0.81	0.73	0.65	0.58

taining a low carbon content corresponding to the SAE 4615-4620 specification is carburized. The Timken Roller Bearing Company furnished a series of induction-furnace heats of steel with increasing carbon content with which this part of the research was carried out.

14. *Materials.*—The like heats which were further examined are bars 10 to 15 whose analyses and hardenability-test results are given in Tables 4 and 5. The microstructures of this series of like heats are shown in Fig. 6 along the rolling direction in the as-received condition at a magnification of 200 diameters. The microstructures of the hypereutectoid region of the McQuaid-Ehn test samples for grain size of bars 10-15 are shown in Fig. 7 along the rolling direction at a magnification of 500 diameters.

The analyses of the induction furnace heats of like analysis (except for carbon) and approximately like total alloy are given in Table 6. These bars were hot rolled, annealed at 1650 deg. F., and furnace cooled.

15. *Test Procedure.*—The Jominy test specimens of bars 10 to 15 which were already carburized and end-quenched were ground along the length of the bar to depths as follows: 0.005, 0.010, 0.020, 0.030 inch in addition to the two surfaces of 0.015- and 0.026-inch depths already prepared for previous hardenability tests. Progressive hardness surveys were made in the same way as for the 0.015- and 0.026-inch depths on the new surfaces from the water-cooled to the slowly-cooled end of the bar. These tests for depths of 5 to 30 thousandths were designed to provide information as to the depth in the bar at which maximum hardenability is attained. It was desirable to determine along with these hardness tests at various depths what carbon content existed in the bars at these depths, and also whether a serious difference in the carbon gradients of the various bars is established in the eight hours of carburizing at 1700 deg. F. One-inch diameter bars of the like heats were prepared in six-inch lengths and carburized at 1700 deg. F. with time and procedure the same as for the Jominy bars. The carburizing boxes were removed from the furnace and cooled to room temperature before removing the samples. The bars were then placed in a lathe between the same centers as had been used previously in preparing the bars for carburizing, and cuts were made for a total of eight cuts of 0.005-inch depth for each cut. The carbon analyses were carried out in the Research Laboratories of the Timken Roller Bearing Company.

Table 7
Analyses and Hardenability of Induction Furnace Steels

Bar	Content, per cent								Total Alloy per cent	Grain Size	Jominy Bar Hardenability (Carburized)	
	C	Mn	Si	Cr	Ni	Mo	P	S			at 0.015-in. Depth in.	at 0.026-in. Depth in.
Z1	0.63	0.50	0.27	0.26	1.74	0.24	0.013	0.018	3.01	5-8	¾ +	1 +
Z2	0.71	0.50	0.31	0.21	1.74	0.26	0.011	0.018	3.02	5-7	1	1½ +
Z3	0.76	0.50	0.28	0.23	1.73	0.26	0.015	0.023	3.00	6-8	1¼ +	1½ +
Z4	0.78	0.50	0.25	0.19	1.74	0.24	0.014	0.020	2.92	4-7	2 +	2½
Z5	0.84	0.50	0.25	0.20	1.74	0.25	0.014	0.021	2.94	4-7	2½	2½
Z6	0.88	0.51	0.25	0.24	1.71	0.25	0.014	0.021	2.96	5-7	2½	2½
Z7	0.94	0.49	0.24	0.22	1.72	0.24	0.014	0.020	2.98	5-7	2½	2½
Z8	1.00	0.47	0.24	0.23	1.73	0.25	0.013	0.020	2.92	4-7	1½ +	1¾
Z9	1.05	0.52	0.25	0.23	1.74	0.26	0.013	0.020	3.00	5-7	1¼ +	¾ +
Z10	1.08	0.50	0.24	0.23	1.73	0.25	0.014	0.020	2.95	4-7	− ⅛	− ⅛
Z11	1.16	0.50	0.25	0.23	1.75	0.24	0.014	0.021	2.97	5-7	⅛	⅛
Z12-8*	0.22	0.56	0.28	0.14	1.73	0.25	0.012	0.018	2.96	...	¼ +	− ⅛
Z12-10*	....	....	....	....	....	....	.....	.....	....	...	¾ +	½ +
Z12-12*	....	....	....	....	....	....	.....	.....	....	...	1 +	¾

*This figure denotes the number of hours carburized.

The quenching tests on the induction furnace heats, Z1 to Z11 of Table 7, consisted of preparing Jominy specimens, heating them in cast iron chips for one hour at 1700 deg. F., and end-quenching in the regular manner. The bars were then ground to depths of 0.015- and 0.026-inch and surveyed for hardness.

Specimens from bar Z12, which had been melted in the induction furnace to duplicate the like heats of bars 10 to 15 for a comparison of the carburized hardenability of induction furnace heats with that of the commercially-prepared heats, were carburized and quenched according to the Jominy procedure. A low hardenability was obtained, and the effect of an increasing carbon content was, therefore, investigated by increasing the carburizing time for other specimens prepared from the same bar.

To compare the prediction given by the Jominy test with the hardenability which would be obtained for a bar of the same material carburized and actually quenched as for commercial procedure, there were prepared six-inch specimens one inch in diameter from bars 10 to 15. These specimens were carburized, using the same time and procedure as for the Jominy bar, and then quenched in oil at room temperature. The quench in oil of a one-inch round bar produces a surface cooling rate approximately the same as that existing in the Jominy bar at a distance of $\frac{1}{8}$ inch from the water-cooled end.* Comparisons of the hardenability of these two types of specimens are given for bars 10 to 15 in Fig. 23.

In order to determine the hardness at closely-spaced intervals on the specimens quenched in oil, it was necessary to provide a hardness-testing surface tapered from the outside to depths down to 0.030 inch. This taper was provided by grinding the bar at a slope of $\frac{1}{64}$ inch per inch. Every $\frac{1}{8}$-inch interval on the hardness testing surface was therefore equivalent to a change of 0.001953 inch or practically 0.002 inch of depth.

16. *Test Data.*—Hardness values for various depths in Jominy test specimens of bars 10 to 15 are summarized in Fig. 8. The results are shown in these curves for hardness versus depth in the bar for each $\frac{1}{4}$ inch from the water-cooled end.

The carbon gradient tests on bars 10 to 15 are given in Table 6 and Fig. 9. The curves were obtained by plotting the carbon content of the first cut of 0.005 inch on the abscissa value for half the depth of the cut, i.e., 0.0025 inch (average depth), and likewise for the total

*H. J. French. The Quenching of Steels (1930) and reference (1) of the bulletin.

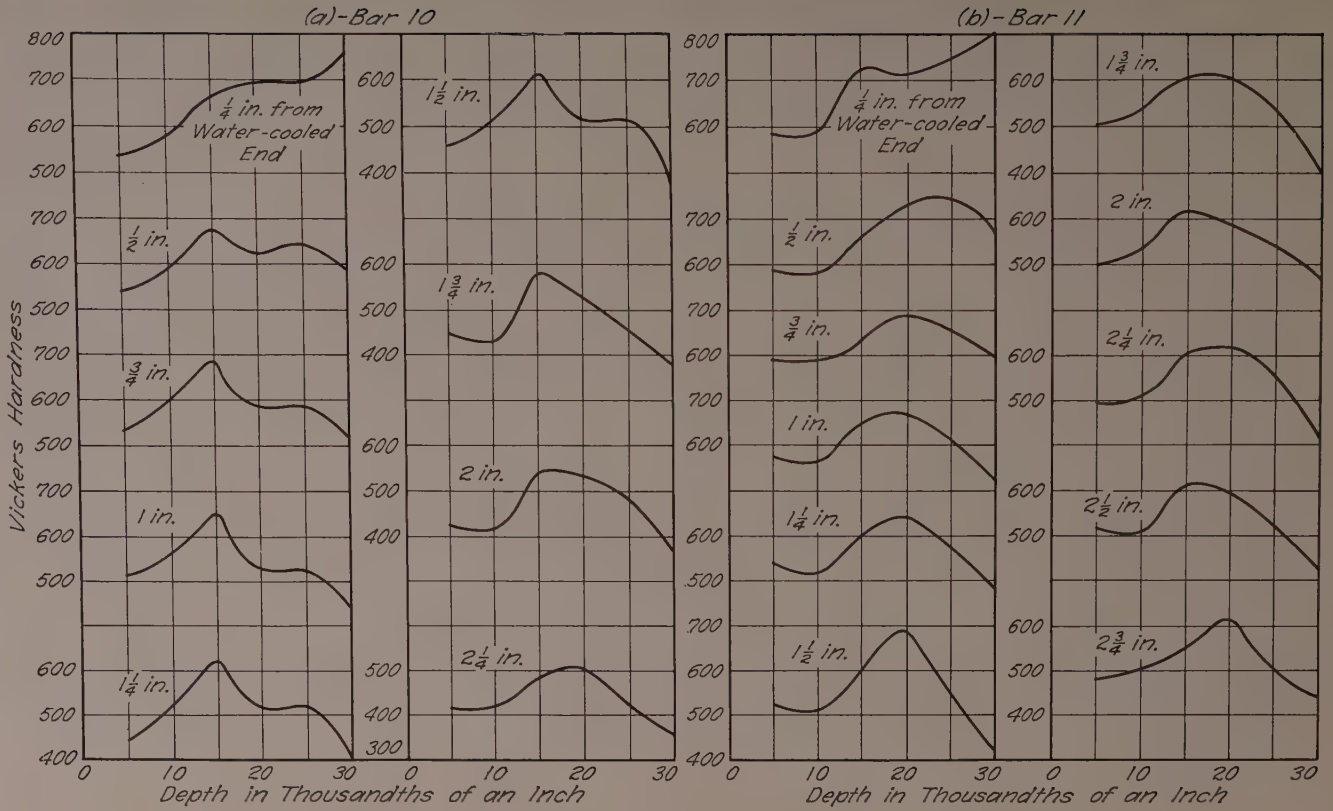

FIG. 8. HARDNESS VERSUS CASE DEPTH AND DISTANCE FROM WATER-COOLED END OF BARS 10 TO 15

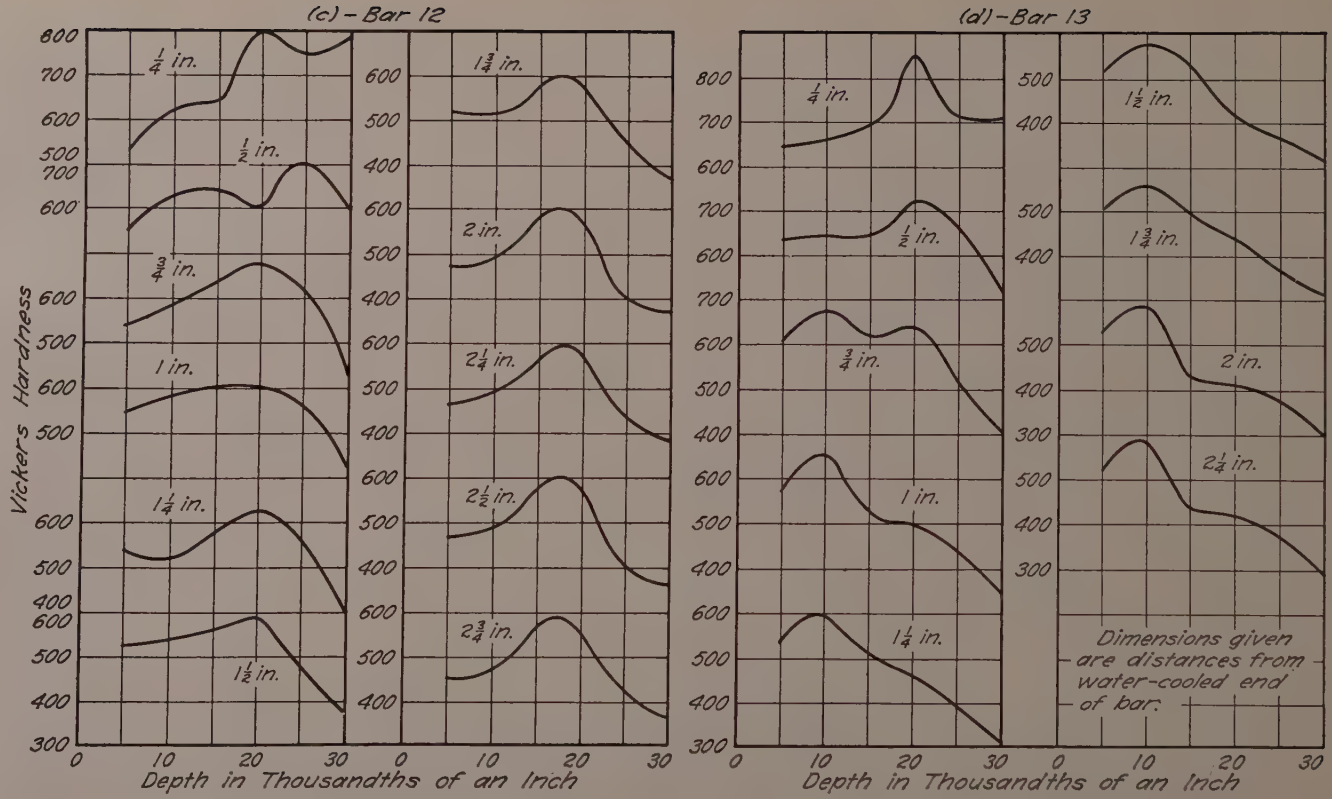

FIG. 8 (CONTINUED). HARDNESS VERSUS CASE DEPTH AND DISTANCE FROM WATER-COOLED END OF BARS 10 TO 15

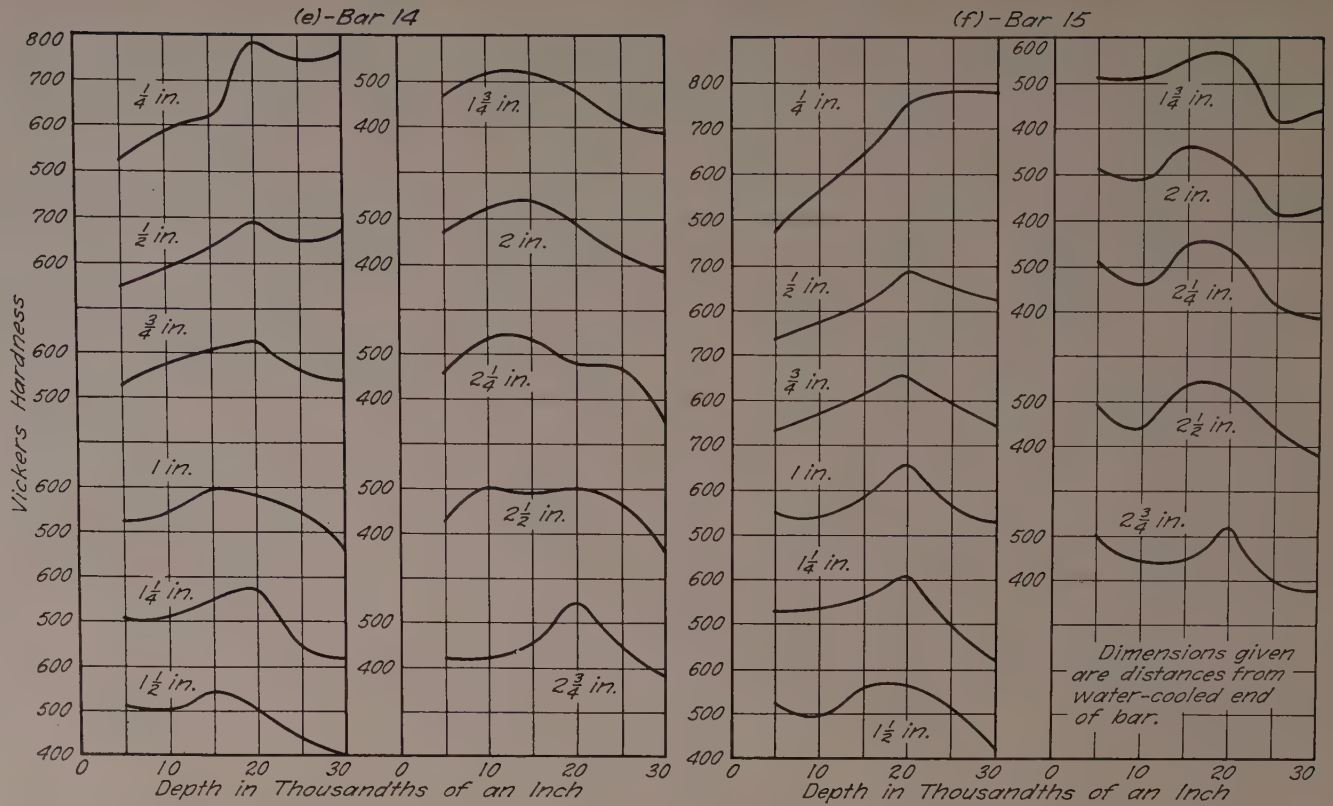

FIG. 8 (CONCLUDED). HARDNESS VERSUS CASE DEPTH AND DISTANCE FROM WATER-COOLED END OF BARS 10 TO 15

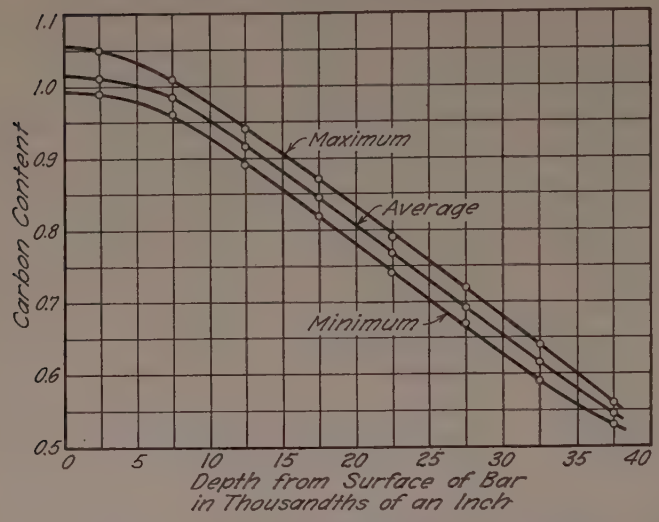

Fig. 9. Carbon Gradient in Carburized Bars of SAE 4615-4620 Steels

of eight cuts made on the bars. A carbon gradient test for bar 29 was included with this series because the bar showed a low hardenability and it was of interest to determine whether its carburizing behavior was responsible. A study of the individual curves together with a consideration of the probable errors in the actual carbon analysis, machining of cuts, etc., indicated that the series of tests should be regarded as a group rather than individually. Accordingly a curve was drawn for the maxima and minima of the series and for the average carbon gradient.

Jominy hardness-test results on specimens from the induction furnace heats Z1 to Z11 which were heated to 1700 deg. F. and end-quenched are shown in Table 7 and Figs. 10, 11, and 12; Fig. 12 is plotted as inches of hardenability versus carbon content.

Bar Z12 whose analysis is included in Table 7 was tested for hardenability when carburized for 8, 10, and 12 hours. The results are given in the curves of Figs. 11 and 13, and at the bottom of Table 7.

The results of tests made on carburized one-inch round samples of bars 10 to 15 quenched in oil from the carburizing temperature are given in Fig. 23, together with the results on the corresponding Jominy bars $\frac{1}{8}$ inch from the water-cooled end at depths of 0.005 to 0.030 inch.

17. *Discussion of Data on Hardenability of Like Heats of SAE 4615-4620 Steels.*—The contours for hardness versus case depth and

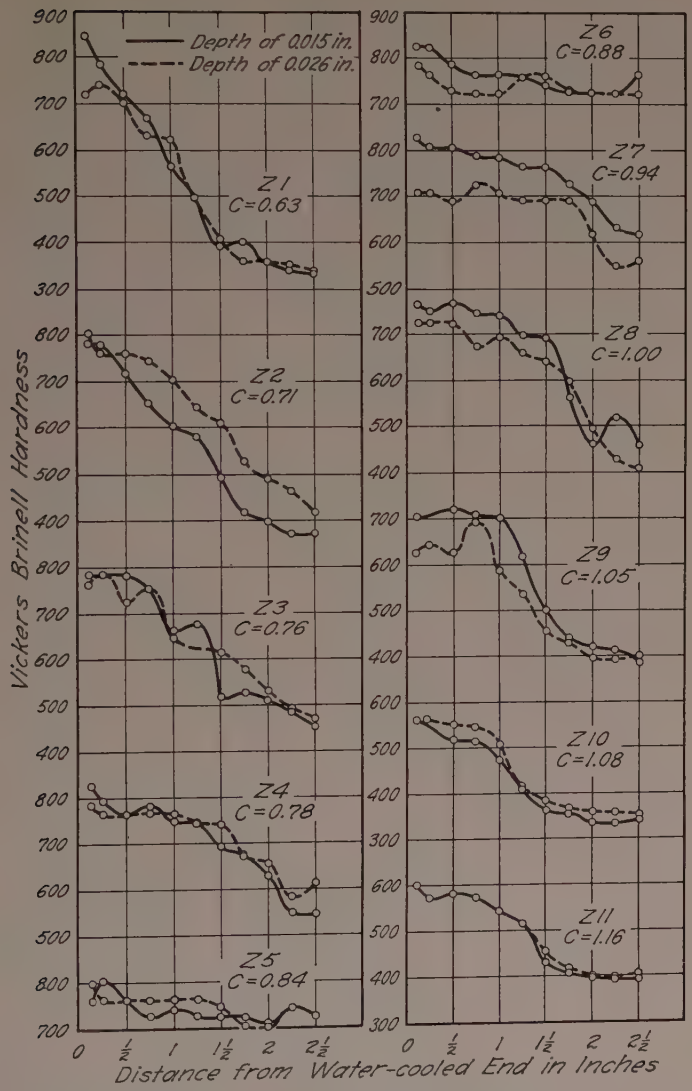

FIG. 10. HARDENABILITY OF UNCARBURIZED INDUCTION FURNACE HEATS WITH INCREASING CARBON

distance from the water-cooled end of the bars 10 to 15 shown in Fig. 8 indicate a peak hardness which varies as to the depth at which it occurs, as to the distance from the water-cooled end, and as to the bar under consideration. Bar 10 has a peak at 0.015-inch depth, bar 11 at 0.020-inch depth, bar 12 at 0.020-inch depth in general, bar 13

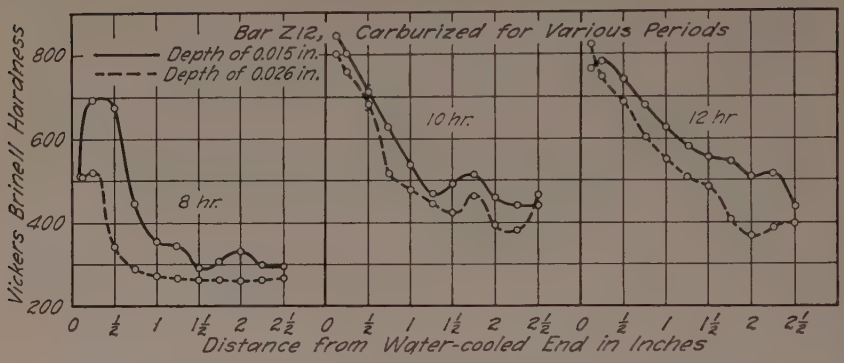

FIG. 11. HARDENABILITY OF CARBURIZED INDUCTION FURNACE HEATS

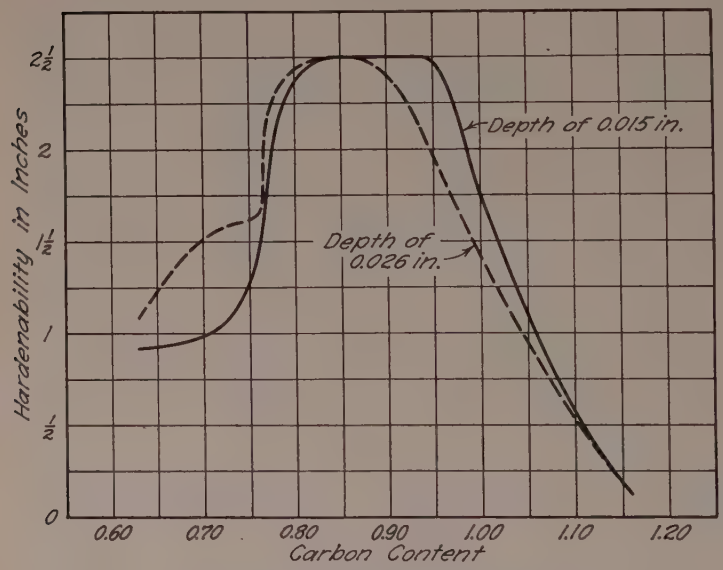

FIG. 12. HARDENABILITY VERSUS CARBON CONTENT FOR BARS OF INDUCTION FURNACE HEATS

at 0.010-inch depth, bars 14 and 15 at 0.015- to 0.020-inch depth. In cases where the peak occurs at 0.015-inch depth the Jominy method of specifying hardness at the arbitrary 0.015-inch depth is correct, but the other bars are incorrectly rated by the Jominy test. For example, Table 8 compares the hardenability for the various bars obtained by Jominy's method and that obtained by the more complete survey summarized in the curves of Fig. 8. Bars 10, 12, 13, 14, and 15

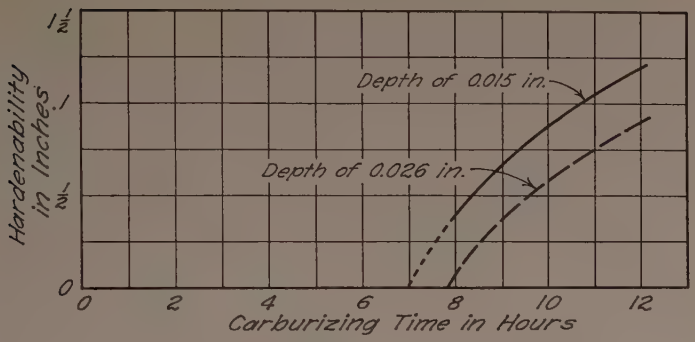

FIG. 13. HARDENABILITY VERSUS CARBURIZING TIME FOR Z12 BAR OF INDUCTION FURNACE HEAT

TABLE 8
COMPARISON OF JOMINY-TEST WITH MAXIMUM HARDENABILITY

Bar	Jominy-Test Hardenability		Maximum Hardenability from Figs. 20-25	
	at 0.015-in. Depth in.	at 0.026-in. Depth in.	Distance from Water-cooled End in.	Depth in.
10	1½	¾	1½	0.015
11	2½	1	2½	0.020
12	1 +	¾ +	1¼	0.020
13	¾ +	½ +	1¼	0.010
14	1	½	1	0.015
15	¾ +	¾	1¼	0.020

have a somewhat more uniform hardenability than was indicated by the tests at 0.015- and 0.026-inch depths only. The curves for bar 12 in Fig. 8 would also indicate that if hardness tests had been made at a depth of approximately 0.0175 inch the hardenability for the bar would probably have extended to 2¼ inches.

The tests made to determine the carbon gradient established by the carburizing procedure as shown in Table 6 and Fig. 9 indicate that the carbon gradient and carbon contents are substantially the same for all of the bars examined. The range in which maximum hardenability is obtained is from 0.010- to 0.020-inch depth, as seen in Table 8, and these depths correspond to an average carbon content of 0.95 to 0.81 per cent from Table 6. It is therefore possible to state that the maximum hardenability at different depths is associated with a definite range of carbon content.

The results of tests on the induction furnace heats Z1 to Z11

shown in Table 7 and Figs. 10, 11, and 12 indicate that full hardening is obtained for a range of carbon contents from 0.94 to 0.78 per cent when there is no carbon gradient such as exists in a carburized bar. Since the carburized bars have a carbon content within this range at depths of 0.010 to 0.020 inch, they also might be expected to harden to the full 2½ inches because they are the same type of steels as the Z1 to Z11 bars. However, the results from tests on the induction furnace heats presented in Fig. 12 show that for steels with above 0.94 per cent and below 0.78 per cent carbon a lower hardenability is obtained. The lower hardenability is a result of the formation of substantial amounts of high temperature products of the decomposition of austenite. On quenching from 1700 deg. F. the austenite of these steels has a maximum stability in the range of 0.94 to 0.78 per cent carbon content. In a bar of SAE 4615-4620 steel subjected to the Jominy test the austenite is of variable stability due to the carbon gradient established by carburizing, and the austenite with the carbon range for maximum stability is interposed between austenites of lower stability. The high temperature austenite transformation products can therefore grow into the more stable austenite both from the high carbon and the low carbon side, respectively, with more than 0.94 per cent and less than 0.78 per cent carbon. Apparently in some of the steels subjected to the Jominy test this growth of austenite decomposition products is so rapid as to nucleate the decomposition of the austenite which normally would have a high stability in the range of 0.94 to 0.78 per cent carbon content if it were exclusively present in the steel.

The comparison of the hardenability of the induction furnace heats with the carburized bars used in the Jominy test raises the question as to the possibility of obtaining 600 (or higher) Vickers-Brinell hardness for all of the steels in Tables 4 and 5 with the cooling rate existing at 2½ inches from the water-cooled end of the Jominy bar, if the carbon content were in the range of 0.94 to 0.78 per cent without the presence of neighboring higher and lower carbon contents such as actually exist in the carburized bars. A partial answer to this question is given in the results of hardenability tests on the Z12 bar which, when carburized for eight hours, gave a low hardenability, and, when more carbon was added, gave an increased hardenability, as shown in Fig. 11 and Fig. 13. In discussing the results for bar Z12 carburized for 8, 10, and 12 hours it must be noted that the carbon content at the surface of the bar in eight hours of carburizing at 1700 deg. F. is at a maximum which will not be increased with additional carburizing time. Therefore, the additional carburizing time has the effect of increasing the penetration

of carbon into the core. From Table 6 the carbon content at 0.015- and 0.025-inch depth should be on the average, respectively, 0.89 and 0.73 per cent. The latter is below the range of carbon content of maximum hardenability for this type of steel, and the additional carburizing time is believed to have been effective in increasing the hardenability at 0.015-inch depth merely due to the enhanced stability given to the austenite at greater depths. Likewise the increase in hardenability with carburizing time for the 0.026-inch depth is apparently due to the increased stability of austenite in the portions of the bar at depths greater than 0.026 inch as a result of the higher carbon concentration. It may be of interest to extend the tests on bar Z12 to determine the carbon content and carburizing time required to produce a hardenability of 2½ inches at the 0.015-inch depth. The reason for the lower stability of the austenite in different bars of SAE 4615-4620 steels beyond the range of carbon content for maximum hardenability is not apparent from the foregoing tests. An investigation of the microstructures produced by the varying quenching rates provided in the Jominy tests of the like heats, bars 10 to 15, was therefore considered to be of value in attempting to establish the cause for varying austenite stability in different heats of the same type of steel.

18. *Discussion of Microstructure of Jominy Bars of Like Heats—Bars 10 to 15.*—The photomicrographs shown in Figs. 14 to 18 at a magnification of 1000 diameters were taken at the 0.015-inch depth at ¼, 1¼, 2 and 2½ inches from the water-cooled end of bars 10 to 15 which had been carburized and end-quenched. At a distance of ¼ inch, as shown in Fig. 14, the structures are all martensitic with small amounts of retained austenite. All the structures are similar except for bar 12 which has a somewhat coarser martensite.

At the 1¼-inch distance, Fig. 15, we find some evidences of austenite instability in each bar as shown in the non-martensitic areas where the austenite has transformed at a higher temperature. The black areas where the austenite has transformed to upper bainite are most in evidence in bars 10, 13, and 14, while bars 11, 12, and 15 are similar and therefore indicate practically identical austenite stability at this distance and depth.

At the 2-inch distance, Fig. 16, the transformation of austenite at the higher temperatures has progressed considerably in all bars except 11, for the black areas have greatly increased in extent in bars 10, 12, 13, 14, and 15, but to a lesser extent in bar 11.

At the 2½-inch distance, as shown in Fig. 17, there is little change

FIG. 14. MICROSTRUCTURES AT 0.015-INCH DEPTH AND ¼ INCH FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

FIG. 15. MICROSTRUCTURES AT 0.015-INCH DEPTH AND 1¼ INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

FIG. 16. MICROSTRUCTURES AT 0.015-INCH DEPTH AND 2 INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

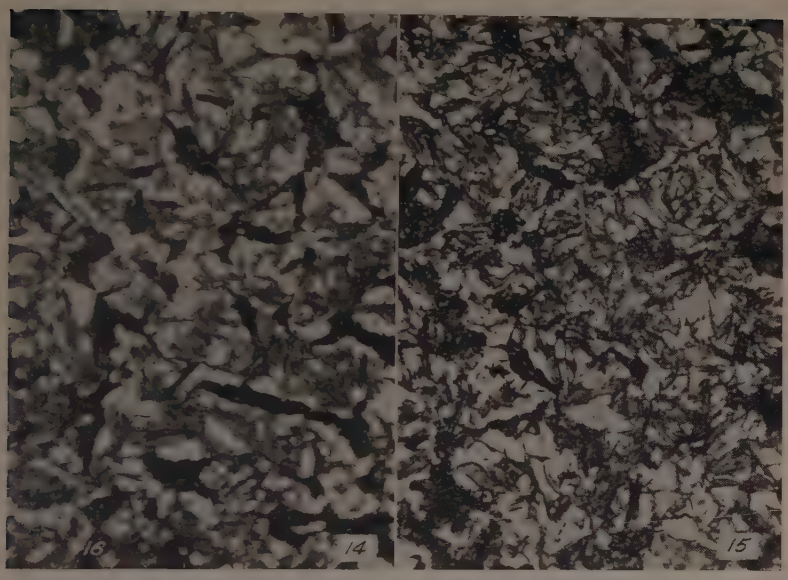

FIG. 16 (CONCLUDED). MICROSTRUCTURES AT 0.015-INCH DEPTH AND 2 INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

except in bars 10 and 11 where there appears to have occurred a slightly increased austenite transformation at the higher temperature.

In all of the photomicrographs at 2 and 2½ inches from the water-cooled end it was difficult to choose a representative field since closely adjacent areas showed considerable contrast in the amount of martensite and transformed austenite. This contrast was of varying degrees in the different bars, but appeared to be highest in bar 15. Figure 18 shows areas of bar 15 closely adjacent to the field of the same bar shown in Fig. 17. In Fig. 18a is an area which indicates that a larger amount of martensite has formed than is seen in the field of bar 15 in Fig. 17, while Fig. 18b shows almost complete transformation at the higher temperatures with practically no martensite formed. The reason for the lack of uniformity of microstructure is indicated by the photomicrographs in Fig. 19, which were taken at the 2½-inch distance from the water-cooled end of the bar and at the 0.015-inch depth. These photographs are at a magnification of 50 diameters, and show bands of dark and light areas which are parallel to the longitudinal axis of the bar. In the darker areas the austenite has transformed more completely at the higher temperatures than in the lighter areas in which

FIG. 17. MICROSTRUCTURES AT 0.015-INCH DEPTH AND 2½ INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

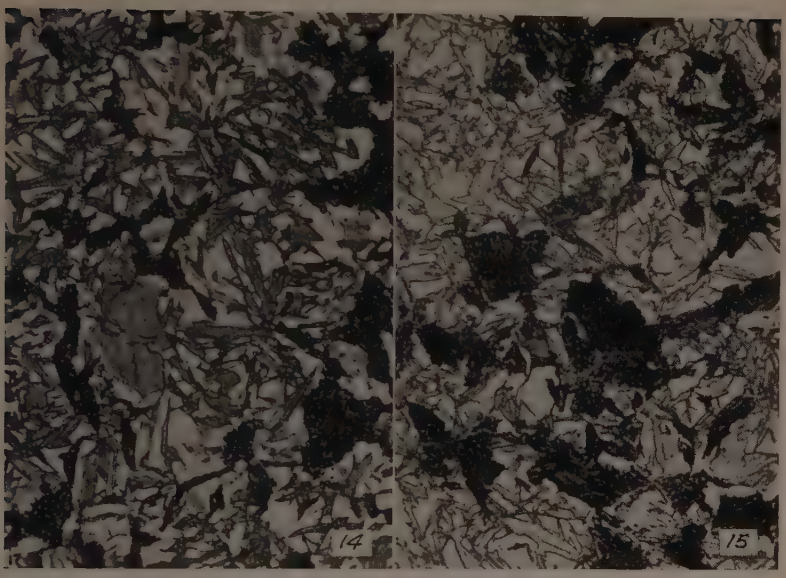

FIG. 17 (CONCLUDED). MICROSTRUCTURES AT 0.015-INCH DEPTH AND 2½ INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 1000X

FIG. 18. VARIATION IN MICROSTRUCTURE OF BAR 15 AT 0.015-INCH DEPTH AND 2½ INCHES FROM WATER-COOLED END AT MAGNIFICATION OF 1000X

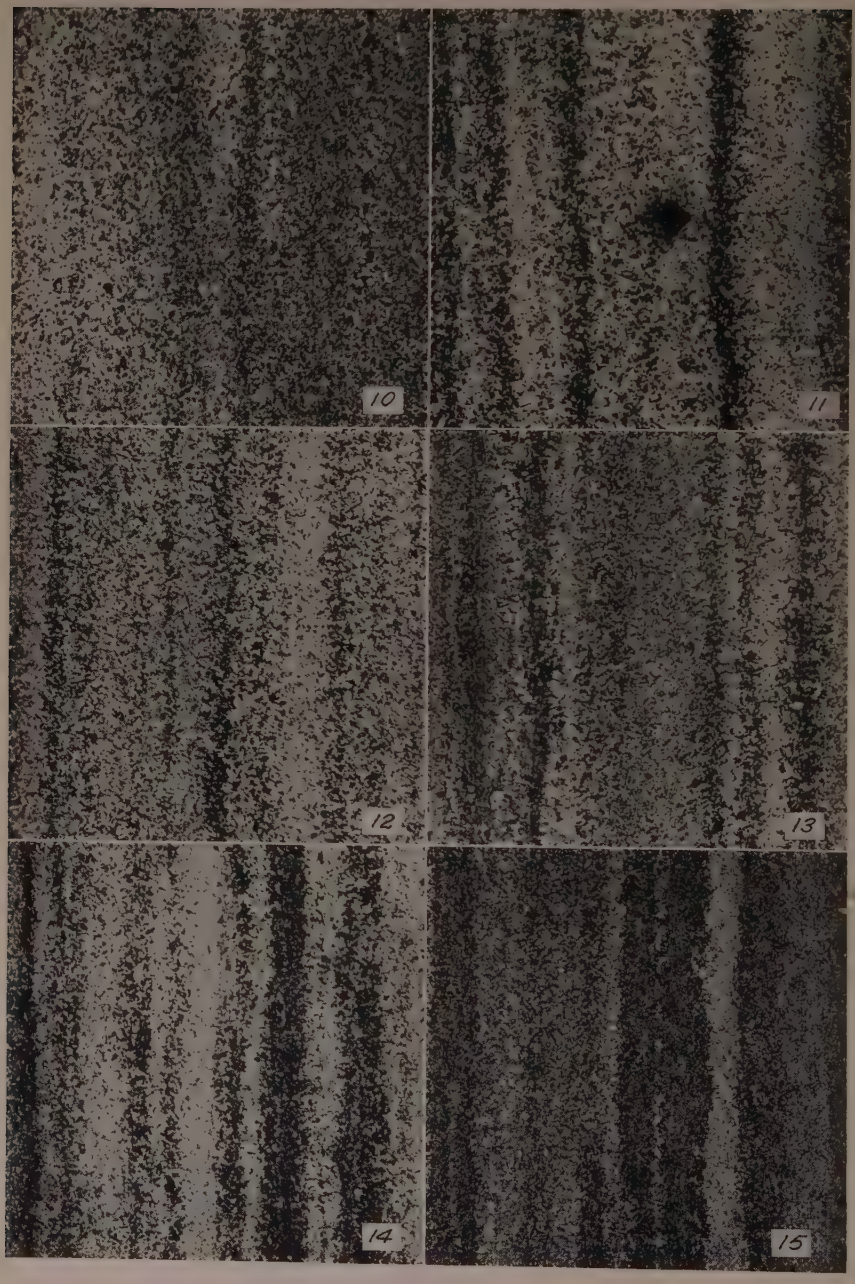

FIG. 19. MICROSTRUCTURES AT 0.015-INCH DEPTH AND 2½ INCHES FROM WATER-COOLED END OF BARS 10 TO 15 AT MAGNIFICATION OF 50X

martensite is present. It is significant that all the bars, including bar 11, which had the highest hardenability of the group of like heats, show the presence of the banded areas.

Since the bands of high transformation products and martensite are of low and high hardness respectively, it is possible for the indent of the Vickers-type hardness-testing machine to be located by chance in an area of low hardness or high hardness, thus leading to erratic hardness values in the portions of the bar where the banded areas occur. The indent for the 2½-inch distance in bar 11 has purposely been included in Fig. 19 to indicate the possibility of erratic values being obtained in the Jominy test, since it can be seen that a shift of the indent slightly to the left or right of its position would locate it in the darker bands of lower hardness. This is actually the case for many of the bars shown in Fig. 4 where erratic hardness readings were obtained, and subsequent tests on bar 15 showed that a hardness of 613 Vickers-Brinell could be obtained near the 2½-inch distance while closely adjacent areas gave readings as low as 383.

Bars 10, 12, and 13 have the most uniform appearance in Fig. 19 indicating a fairly uniform austenite instability at 2½ inches and the 0.015-inch depth. On the other hand bars 11, 14, and 15 show pronounced evidence of localized low-stability of the austenite in the darker bands. The width of the bands decreases in the order 15, 14, 11, which is the same as the order of hardenability (Table 5) for these steels. Bar 10 is also less banded than bar 12, and has a higher hardenability, but bars 10 and 12 have less evidence of banding than bar 11, which has the highest hardenability.

The presence of banding is also indicated in the photomicrographs of the "as received" steels of bars 10 to 15, as shown in Fig. 6. The most pronounced banding occurs in bars 10, 14, and 15. The bars 14 and 15 show a whiter ferrite free from etching constituents such as are present in the ferrite of bars 10 to 13. There is no characteristic difference between bar 11 and bars 12 and 13 which would indicate the reason for the high hardenability that is obtained for bar 11.

The existence of banding in steels has been associated in the literature (references 3, 4, 6) with the original dendritic structure of the ingot where segregation of inclusions or chemical segregation occurs at the dendrite boundary, and is then rolled out into elongated areas containing the segregated material. In Figs. 20 and 21 the steels of bars 10 to 15 show in the polished and unetched condition the presence of so-called "stringers" or elongated areas of inclusions which are oriented in the rolling direction. The inclusions found in

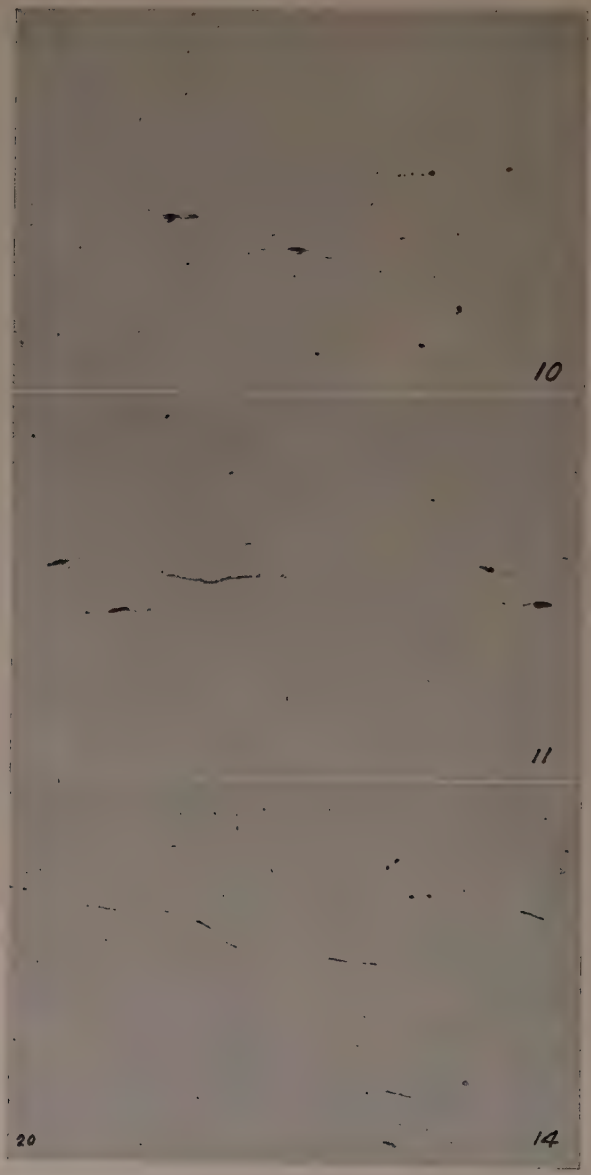

FIG. 20. DEOXIDATION TYPE INCLUSIONS IN VARIOUS BARS AT MAGNIFICATION OF 200X

FIG. 21. DEOXIDATION TYPE INCLUSIONS IN VARIOUS BARS AT MAGNIFICATION OF 1000X

these steels are of the deoxidation type, and two of the bars, 11 and 14, have been examined by Mr. R. K. Lee, Research Engineer of the Timken Laboratory, with the following results, on a percentage basis:

	SiO_2	Al_2O_3	FeO	MnO
Bar 11	0.0008	0.0031	0.0015	0.0001
14	0.0008	0.0032	0.0016	0.0001

A petrographic examination of the inclusions separated from the steels by means of the special methods developed by the Timken Laboratory showed a very large amount of alumina inclusions, a small amount of glassy inclusions with a refractive index of 1.51, and a very small amount of glassy inclusions with a refractive index of 1.48. The bars 11 and 14 have closely checking values for the chemical contents of the inclusions, thus indicating close control of the furnace and deoxidation practice. According to the experience of the Timken Roller Bearing Company it is reasonable to assume that since the same control was used in melting and deoxidizing the remaining bars of the like heats of steel melted in the same furnace, they will show a similarity in the analysis of the inclusions. However, it cannot be assumed that since the analysis of the inclusions is the same the distribution and size of the inclusions will be the same in each bar. The distribution and size will be affected by length of time the steel is in the ladle, pouring temperature, cooling rate of the ingot, and the rolling operation, in which there may be sufficient variation to promote differences in the distribution pattern of the inclusions in the steel.

The effect of inclusions and banding are important in this study since it has been found that low hardenability in localized areas of the Jominy bars occurs in bands where the austenite has transformed at higher temperatures. Other areas which appear to have a lesser number of the small alumina inclusions have a higher austenite stability and harden to a higher degree. Differences in the dispersion of the inclusions and their size may then account for the differing hardenabilities obtained in steels of the same type, chemical analysis, grain size, and inclusion analysis, since this study has shown that the transformation of austenite at the higher temperature takes place first at surfaces of the inclusions at the depths corresponding to the carbon range for maximum hardenability. Proof of this assertion is given in Fig. 22, which shows micrographs of bar 11 at the 0.015-inch level, and at approximately ¾ to one inch from the water-cooled end. The photomicrographs are at a magnification of 4200 diameters, and show the inclusions with the black areas of high-temperature transformation

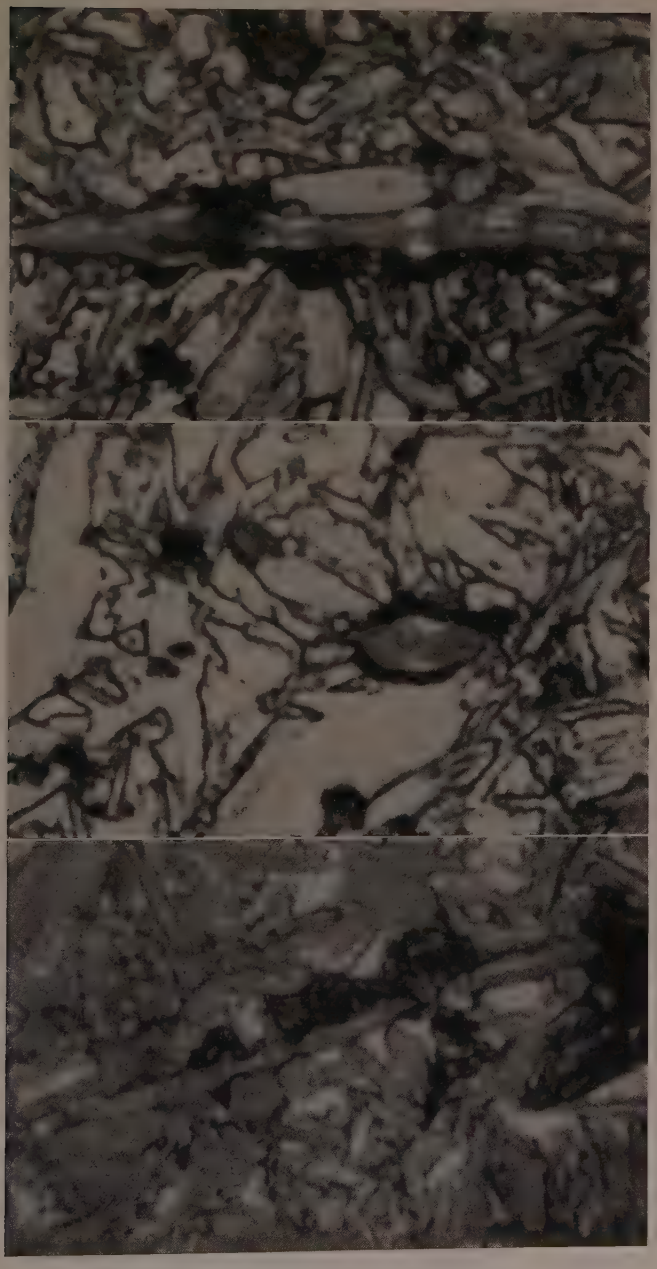

FIG. 22. AUSTENITE TRANSFORMATION AT HIGH TEMPERATURES STARTING FROM INCLUSIONS; MAGNIFICATION 4200X

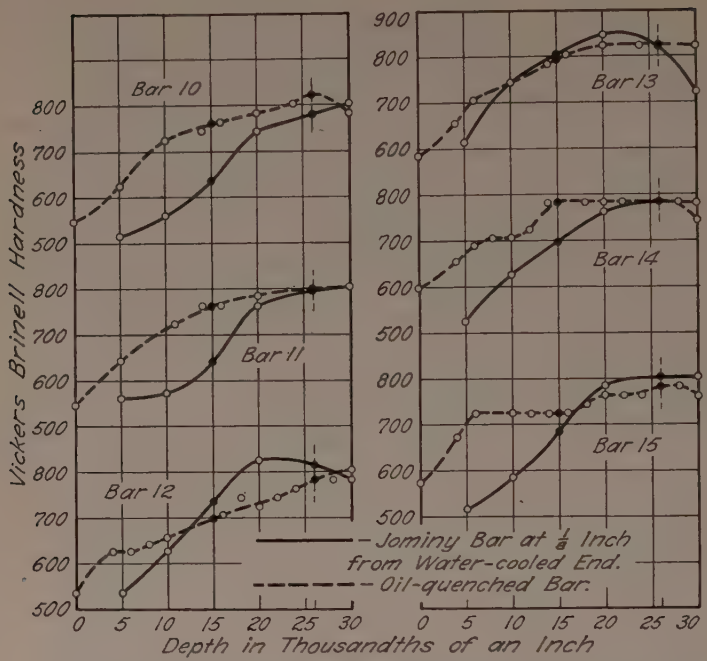

FIG. 23. COMPARISON OF JOMINY BAR HARDENABILITY AT 1/8 INCH FROM WATER-COOLED END WITH HARDENABILITY OF CARBURIZED BAR QUENCHED IN OIL FROM 1700 DEG. F.

products starting from the surface of the inclusion, the rest of the structure being martensite.

The more uniformly the inclusions are dispersed, the more effective they would appear to be in promoting a low austenite stability in the whole volume in the Jominy bar. On the other hand, the restriction of the inclusions to narrow bands or stringers would restrict low hardenability or austenite instability to a small volume of steel surrounding the stringer or band, and would permit the areas comparatively free from such inclusions to harden to a higher degree. Inclusions of very small size if uniformly dispersed provide a larger surface area which may be more effective in promoting austenite instability over a larger volume of the steel than the same total amount of inclusions of larger particle size. Such variation in the distribution of inclusions is shown in Figs. 20 and 21, where bars 10 and 14, which have a lower hardenability than bar 11, have a more uniformly dispersed distribution of the inclusions. The inclusions in bar 11 are in larger stringers without the presence of a large number of the smaller inclusions, such as are present in bars 10 and 14.

TABLE 9

COMPARISON OF JOMINY BAR HARDENABILITY AT 1/8 INCH WITH HARDENABILITY OF CARBURIZED BAR QUENCHED IN OIL FROM 1700 DEG. F.

Bar	Hardness at 0.015-in. Depth			Hardness at 0.026-in. Depth		
	Jominy Bar	Oil Quenched Bar	Difference	Jominy Bar	Oil Quenched Bar	Difference
10	635	762	127	780	824	44
11	640	762	122	795	800	5
12	735	698	+37	818	782	+36
13	803	795	+ 8	820	827	7
14	698	782	84	781	782	1
15	685	727	42	803	782	+21
Maximum difference for the series of bars	168	84		40	45	

Note: In the difference columns the plus sign indicates a higher hardness for the Jominy bar.

Quantitative determinations of particle size of the inclusions and their distribution have not been made since an intensive study of these factors is contemplated for further research in the problem of hardenability. The possible effect of chemical segregation in producing areas of lower austenite stability will also be investigated by means of various heat treatments of the Jominy bar prior to carburizing.

19. *Discussion of the Data on Predictability of Hardenability by Means of the Jominy Bar.*—The curves of Fig. 23 summarize the data obtained in a study of the hardenability predicted by the Jominy bar hardness contours at 1/8 inch from the water-cooled end. The degree to which the curve for the oil-quenched bar can be superimposed on the Jominy test hardness contour is a measure of the accuracy of the Jominy hardenability prediction. In general the curves are in close correspondence at the 0.026-inch depth, but at the 0.015-inch depth there is a considerable spread in the values for all except bar 13. An analysis of these curves has been put into Table 9, which shows the spread in values obtained. As indicated in Table 9, the correspondence between the hardenability test performed on a bar actually put through the carburizing and hardening operation and the Jominy bar is fair if we consider the 0.026-inch depth only. The Jominy bar predicted an extreme difference of 40 Vickers-Brinell units for the six bars at the 0.026-inch depth, while the actual extreme difference was 45 units. For the 0.015-inch depth the Jominy bar predicted a maximum difference for the six bars twice as great as that actually found. The steels are therefore more uniform than they would appear to be from the

TABLE 10

COOLING RATE AT VARIOUS DISTANCES FROM WATER-COOLED END COOLED FROM 1700 DEG. F. (JOMINY AND BOEGEHOLD)

Distance from Water-cooled End in.	Rates of Cooling, deg. F. per second		Time in Seconds to Cool to 900 deg. F.	Time in Seconds to Cool from 1000 to 900 deg. F.
	at 1300 deg. F.	at 1000 deg. F.		
1/16	420	420	2	0.44
3/16	93	42	12	4.9
5/16	61	24	24	8
9/16	25	12.5	42	16
1 3/16	12.5	8.1	66	24
1 5/16	7	5	123	40
2 1/2	4.5	2.7	220	76

Jominy test. For bars 12 and 13 the Jominy-bar curves show a peak hardness at 0.020 inch, which is a higher hardness than is developed in the corresponding oil-quenched bars for the depths tested. Since hardness was not determined at greater depths than 0.030 inch it is not known whether the curves which do not show peaks would have shown an appreciably higher hardness at depths below 0.030 inch.

In considering the differences in hardenability shown in Fig. 23 and Table 9 it is seen that the greatest differences are obtained at the outside of the bar. Since the cooling rates here are substantially the same for the two bars, according to Jominy's investigation of cooling rates, it is apparent that some other variable has not been considered. An analysis of the thermal history of any cross section of the Jominy bar cooled from one end can be made as follows, although it must be noted that no actual thermal data have been obtained for the Jominy bar beyond that obtained by Jominy and Boegehold and shown in Table 10:

If the Jominy bar were cooled uniformly at the flat portion of the cup end and no heat loss occurred by radiation and conduction to the atmosphere from the cylindrical surface, the temperature and cooling rate across any section parallel to the water-cooled end would be uniformly the same. However, there is some heat loss from the cylindrical surface, and it is possible that the jet of water which is used to cool the cupped end of the bar does not do so uniformly, but cools the center more rapidly due to the diameter of the jet of water being smaller than the diameter of the cup.

A curve showing the cooling rate versus the distance from the center across any section would therefore depart from a straight line to different degrees varying with the distance of the cross section from the water-cooled end. It will also be noted that near the end of the bar

where the adapter is screwed into the sample, as shown in Fig. 1, there is an additional loss of heat by conduction through the adapter and radiation from the flat end of the bar, thus permitting a slightly higher cooling rate to be attained at the end of the bar than at approximately 2¾ inches from the water-cooled end.

The temperature gradient established in the cross section of the one-inch bar quenched in oil is steeper and in the opposite direction from that for the Jominy bar, since the cylindrical surface of the oil-quenched bar in contact with oil is cooled more rapidly than the center. In the latter case it is possible for the stress, during the quenching operation, to build up to a higher value than for a cross section of the Jominy bar with the same surface cooling rate. Apparently this stress has made it possible to attain a higher hardness at the outside of the oil-quenched bar than for the Jominy bar. The quench that the Jominy bar received is then less drastic at the cross section ⅛ inch from the water-cooled end than that obtained in quenching a one-inch round bar in oil, and it is therefore especially perplexing that a higher hardness is obtained at 0.020 inch for Jominy bars 12 and 13 than for the oil-quenched bars. Further work on the actual determination of cooling rates and effects of stress during quenching will be necessary for a complete explanation of the differences found. A comparison of the microstructures at the same levels in the two bars and X-ray diffraction studies of the amount of retained austenite at different depths will also be of value.

A comparison of the Jominy hardenability for distances of 2½ inches from the water-cooled end with the hardenability of a bar carburized and quenched with a similar cooling rate has not yet been made. However, preliminary studies of the reaction rate at constant, subcritical temperature for the carburized bars have shown that the same microstructure as exists at the 2½-inch distance on the Jominy bar can be reproduced by this means, and it will be a valuable method of studying the effect of the distribution of inclusions and banded areas on the stability of the austenite in the different bars. The results so far obtained on one bar indicate the presence of grain boundary carbides in the highest carbon region near the surface of the bar which apparently nucleate the austenite transformation at higher temperatures. This phenomenon would therefore explain the lower hardenability obtained for the higher carbon region in the Jominy bar at lower rates of cooling than are necessary for the retention of austenite.

VI. Summary and Conclusions

20. *The Hardenability of Carburizing Steels as Determined by the Jominy-Bar Test.*—As a result of this investigation the following conclusions may be drawn:

(1) The results of tests made on various SAE steels in the carburized condition indicate that differences in hardenability are determinable by means of the Jominy test.

(2) In general, the hardenability is greater the higher the alloy content of the steel. Specifically, for the SAE 4615-4620 grade of steel it has been found that higher hardenability is more often obtained when the alloy content is above 2.90 per cent and the chromium above 0.17 per cent, but the desired hardenability of 2½ inches is not assured by satisfying these limits.

(3) For the SAE 4615-4620 steels the indications are that an unfavorable distribution of the inclusions may be more effective in reducing hardenability than is a favorable chemical composition in stabilizing the austenite. It has been shown in the results cited in the bulletin that a series of steels with substantially the same grain size, chemical composition, carbide rejection habit (in McQuaid-Ehn microstructure), and the same amount of inclusions do not harden to the same extent when carburized, due apparently to the difference in the distribution of the inclusions, and possible chemical segregation associated with the inclusions in the various steels.

(4) It would appear, therefore, that, provided a marked reduction in the amount of inclusions or the extent of their dispersion could be made by suitable melting, deoxidation, casting, and rolling methods, without causing a change in the grain size, it would be possible to increase the hardenability of the fine grain SAE 4615-4620 steels. Such application of suitable methods and their effect on hardenability would be desirable as a part of an extended program of cooperative investigation.

(5) The result of comparisons made between the hardenability as found at the ⅛-inch distance in the Jominy bar and the hardenability found for one-inch round carburized bars quenched in oil has shown that the hardenability which the Jominy test predicts is not entirely realized. There is a close correspondence of hardenability for the Jominy bar at ⅛ inch from the water-cooled end and for the oil-quenched bar at a depth of 0.026 inch. The fundamental difference in the cooling rates over the cross section for the Jominy bar and for a bar quenched by total immersion has been suggested as a possible

reason for the differences in hardenability observed. The Jominy bar is so designed as to cool from the center of the cross section with a slight temperature gradient, while the fully-immersed bar cools from the outside surface and with a steep temperature gradient. The transformation of austenite therefore takes place in the latter case in a system of stress while the Jominy bar transformation takes place in a practically stress-free condition.

(6) The comparison of the hardenability of the Jominy bar at 2½ inches from the water-cooled end with bars carburized and cooled at the same rate has not been made.

The same cooling rate as in the Jominy bar 2½ inches from the cooled end could be established in a bar larger than one inch round by quenching in oil or water and in a bar smaller than one inch diameter by an air quench. It would therefore be necessary to determine to what degree the carbon gradient of such carburized bars differs from that of the carburized Jominy bar.

In view of the discrepancies observed between the Jominy-bar hardenability at ⅛ inch and an actual quench of a carburized bar it is reasonable to expect a difference between the hardenability at the 2½-inch distance on the Jominy bar and that of a large carburized bar in which this rate of cooling is duplicated.

It is to be hoped that tests of this nature will be made and the extended data presented in order to completely define the applicability of the Jominy test to the study of the hardenability of carburized sections of various mass.

(7) A comparison of the hardenability results obtained by means of the Jominy test and the Burns test indicates that there is no consistent relationship between them for the SAE 4615-4620-type steels. The Burns test provides a critical cooling rate at the surface of the bar, and is used for steels of low carbon content, while the Jominy test provides a variety of cooling rates and is useful for steels of high carbon content and consequently of lower critical cooling rate. A prediction of the hardenability of the carburized Jominy bar can therefore not be made by means of the simpler Burns test on the uncarburized material.

LIST OF REFERENCES

No.	Reference
1	Jominy, W. E. and A. L. Boegehold. A Hardenability Test for Carburizing Steel. Trans. A.S.M. Vol. 26, pp. 574-599, 1938.
2	Burns, J. L., T. L. Moore and R. S. Archer. Quantitative Hardenability. Trans. A.S.M. Vol. 26, pp. 1-22, 1938.
3	Ziegler, M. Sur la cristallisation du fer alpha. Rev. de Mét., Men. Vol. 8, pp. 655-672, 1911.
4	Carpenter, H. C. H. and J. M. Robertson. The Formation of Ferrite from Austenite. Jour. Iron and Steel Inst. Vol. 123, pp. 345-394, 1931.
5	Carpenter, H. C. H. and J. M. Robertson. Structural Changes in Hypereutectoid Steels on Heating. Journ. Iron and Steel Inst. Vol. 127, pp. 259-300, 1933.
6	Herty, C. H., Jr. Nonmetallic Inclusions in Steel. Trans. A.S.S.T. Vol. 19, pp. 1-40, 1931.
7	Harvey, W. E. and B. Stoughton. Microscopic Study of Effects of Heat Treatment upon Ferrite Banding in Steel. Trans. A.S.S.T. Vol. 20, pp. 177-192, 1932.
8	Mahin, E. G. and E. F. Lee. The Influence of Nonmetallic Inclusions upon the Precipitation of Primary Cementite in Hypereutectoid Steels. Trans. A.S.M. Vol. 23, pp. 382-397, 1935.

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